IRON AND STEEL
INSTITUTE PAPERS

PLANT DESIGN · MANUFACTURE · RESEARCH · DEVELOPMENT

The Effect of Cold-Work on Steel

By J. H. Andrew, D.Sc., and H. Lee, Ph.D.

Sections I and II of this paper, dealing respectively with the Effect of Carbon on the Work-Hardening Properties of Steel, and the Effect of Cold-Work upon Electrical Resistivity in Steel, were published in the June issue of the *Journal* (vol. 165, pp. 145–184). The Foreword and Table I published in that issue are repeated below for convenience.

FOREWORD

The effect of cold-work on metals and alloys has been studied by different workers over many years, and some of the basic principles and facts are well known. For example, plastic deformation takes place in the form of slip by shear, the planes and directions of slip being dependent primarily on the lattice structure of the metal. Deformation gives rise to lattice distortion and grain fragmentation, along with other changes in the properties, notably an increase in hardness and strength. The study of these fundamental principles has led to many theories, amongst which the more recent and perhaps the most attractive one is the theory of dislocation proposed separately by Taylor,[1] Polanyi,[2] and Orowan.[3] In this theory the importance of lattice imperfections and local strain is emphasized, and the process of slip is identified with the propagation of dislocations in the metal crystals or grains. As the degree of cold-work increases, the density of such dislocations increases likewise, but tends to approach a limiting value. On the assumption that work-hardening is directly associated with the density of dislocations, this theory has been used satisfactorily to explain the change in properties of cold-worked metals and alloys, if they are homogeneous and their work-hardening characteristics obey the normal shear-stress/strain criterion. Even so, there seem to be slightly divergent opinions concerning the framework of this theory. For instance, Taylor's mathematical treatment deals mainly with stored energy in terms of lattice distortion, whereas Bragg's calculation[4] is based chiefly on the limiting size of the crystallites. Nevertheless, such divergencies may be relatively unimportant, because the real difference between these two schools of thought is purely a difference in the ' path ' which they have taken. The fundamental assumptions and the final conclusions of the two methods are essentially the same.[5]

The theory outlined above is not expected to apply to a heterogeneous material. Indeed, with certain heterogeneous alloys, the stress/strain relationship may, when deformation proceeds to a certain stage, depart from its normal criterion ; steel is known to be in this category. Thus, the work-hardening behaviour of carbon steels is known to be different from that of pure iron in many respects. With pure iron, the hardness of the specimen increases most markedly at the beginning of deformation ; after this, the rate of increase becomes progressively smaller until the specimen approaches a constant value in hardness. The general characteristics of the work-hardening curve in this case are similar to those of other metals and can be predicted by the dislocation theory. In steel, however, there is an abrupt increase[6] in the strength of the material at about 50–80% reduction by cold-drawing, and the degree of deformation corresponding to this latter increase varies systematically with the carbon content (0·3–0·77%) of the steel. Moreover, cold-worked steels have invariably shown[7] an increase in hardness or strength after tempering at low temperatures, the maximum effect usually occurring on tempering at about 300° C. There are indications that this secondary hardening increases with the carbon content of the steel and is generally more marked if the degree of cold-work initially received by the specimen is greater. ' Secondary ' hardening has not been observed to any appreciable extent with cold-worked pure iron specimens.

When these differences in the work-hardening properties of iron and carbon steels are considered, it seems clear that cold-work on steel may involve other

Manuscript received 12th August, 1949.

Professor J. H. Andrew and Dr. H. Lee are at the University of Sheffield. The co-authors of the following Sections were all at the University of Sheffield when these investigations were carried out.

changes in addition to those which can be explained in terms of the normal mechanism of plastic deformation. Since the most obvious difference between iron and steel lies in the presence of carbon, it was thought that the many 'unusual' features associated with the work-hardening properties of steel may be considered from a metallurgical point of view. It was with this in mind that the authors, in an earlier paper,[8] drew attention to certain features and compared them with the effect of quenching. They advanced the hypothesis that austenite was formed in steel during cold-working.

In the discussion on that paper, the austenite theory was not generally accepted as proved for normal forms of cold-working. There are indications, however, that with dynamic loading where the deformation is extremely rapid and localized, or in the case of working which involves intense heat due to surface friction, the formation of austenite and martensite does occur. At the same time, the various effects of internal strains upon physical and mechanical properties of steel are not sufficiently realized. It was with this in mind that the present work was undertaken, experiments being carried out on a much more extensive scale and covering both normal and rapid rates of cold-working. As a result, the effect of internal strains in ferrite and in cementite upon some of the properties of steel can be differentiated, and it appears that austenite formation in steel is restricted to special forms of cold-working involving either dynamic loading or intense surface friction. In presenting these results, it is hoped that some of the misconceptions in the earlier paper will be rectified.

No attempt is made to review the many publications on this subject, since the bibliography is very extensive and incomplete abstracts could lead only to misunderstandings.

The experiments described were carried out by a number of independent workers, and for this reason the paper is subdivided into Sections in accordance with the investigators concerned.

A number of commercial steels were used in this investigation, and their compositions are listed in Table I. Some of these analyses are incomplete, but it may be helpful to point out that steels *A* to *F* all belong to the plain carbon category, and the chief interest is therefore the respective carbon contents.

With the exception of the experiments described in Sections IV and V, cold-working in the form of wire-drawing was employed throughout. The drawing operation was carried out on a drawing bench fully mechanized and fitted with steel dogs and rotating drums driven by a motor coupled with gears. The drawing speed was approximately 5 ft./min. and dry soap was the only lubricant used. The 'blank rods,' before drawing, were machined to sizes usually between 0·2 and 0·3 in., although sizes up to 1 in. dia. were used when experimental conditions demanded. Tungsten carbide dies were employed, and the die angles varied from 6 to 8° for 1-in. and 12 to 14° for $\frac{1}{4}$-in. holes. Drawing was carried out in steps of $\frac{1}{32}$ in. for $\frac{1}{2}$ to $\frac{1}{4}$-in. dia. bars, although for small wires the reduction per draft was considerably less. To avoid excessive heating during drawing, a jet of cold water was played on to the specimen where it left the drawing die.

The cold-working described in Section V was carried out by compression and that in Section IV by means of a dynamic load impact which reduces the height of the specimen. The various procedures and some of the steels employed which are not given in Table I are described in the two Sections concerned.

Section III—AN X-RAY INVESTIGATION OF INTERNAL STRAINS IN COLD-DRAWN STEELS

With P. E. Brookes, B.Met., Ph.D.

SYNOPSIS

The internal strains in ferrite in cold-drawn steels have been studied by X-ray methods. After cold-working, both the macro-strains (as defined by a change of X-ray ring diameter) and the micro-strains (as shown by X-ray line-broadening) are greater with a high-carbon steel than with a low-carbon iron. In the case of a cold-drawn low-carbon iron the macro-strains across the wire section vary from compressive near the surface to tensile at the centre, as measured in the tranverse direction, such strains being due mainly to the presence of body stresses. With a cold-drawn high-carbon steel, the presence of textural stress gives rise to macro-strains such that the ferrite is apparently under uniform compression in the longitudinal direction and under tension in the transverse direction of the wire. The recovery of the macro-strains on heating is consistent with the dilatation results given in Section I.

It is generally accepted that internal stresses in cold-worked metals can be classified in two groups, macroscopic and microscopic. The second type is mainly associated with heterogeneity of the internal strains and with small crystallite sizes, and is believed to be the cause of the observed line-broadening in the Debye X-ray pattern. The first type, however, is manifested in a change in diameter of the X-ray diffraction rings ; the change of lattice spacing within the crystal is more or less uniform, although it may differ for different crystallographic planes or directions. The magnitude and distribution of macroscopic stresses depend to a large extent upon the mode of deformation. The work described in this Section was mainly concerned with internal strains in cold-drawn wires, and particularly with any difference which may exist between low- and high-carbon steels.

The use of X-rays for the investigation of micro-

strains in metals and alloys has been extensively demonstrated by previous workers, and at present it is probably the only recognized method. Macro-strains can be measured by mechanical and other means, as well as by X-ray diffraction ; each method has its own advantages and disadvantages. It is not within the scope of the paper to discuss the relative merits of the different methods. Since the present work was primarily intended to be of a corroboratory nature, requiring only a qualitative indication of the type and distribution of strains, it was considered that the use of X-ray diffraction alone would suffice.

The X-ray diffraction patterns were recorded on a flat-film, back-reflection camera, fitted with a 0·7-mm. dia. focusing pinhole system, with a specimen-to-film distance of 10 cm. During the exposure the specimen was oscillated through 2½° about an axis perpendicular to the incident X-ray beam. This was necessary to obtain patterns suitable for photometric measurement from strain-free specimens. To ensure identical conditions throughout, this oscillation was adopted in all the exposures. The majority of the work was confined to the measurement of the (211) spacing of ferrite, using CrK_α radiation which reflects at a Bragg angle of 78·1°. In certain cases, the strain values for the (220) spacing, obtained by the use of FeK_α radiation, were also determined.

To avoid corrections for specimen shape, a flat surface was used in all cases. The flat surface was carefully polished and etched, the X-ray beam being directed on to this surface with normal incidence. During cutting and polishing, care was taken to prevent heating of the specimens by keeping them immersed in methyl alcohol. Although the preparation of the flat surfaces might alter the internal stress system of the specimens, it should not affect a general comparison between specimens under similar conditions, especially if the results are taken only as qualitative indications.

Temperature fluctuations in the specimen during the exposure would have a spurious effect upon both the line-broadening and the ring diameters observed, but by placing a thermometer in contact with the specimen and taking frequent temperature readings throughout the exposure, the temperature did not vary by more than 1½° from 18° C. No corrections were considered necessary for such a small variation.

Kodak Process films were employed for recording the diffraction lines and were satisfactory for photometric purposes. Each film was marked with a fine gauge so that any shrinkage occurring during processing could be assessed and corrected. Photometric measurements were carried out on a Hilger microphotometer, readings being taken at intervals of 0·1 mm. The film characteristics were determined by a rotating sector and the calibration curve was linear between opacities of 1·6 and 4·0. In the actual experiments, however, the opacity of the background fell frequently below 1·6 and corrections for the non-linear part of the calibration were made in the line-width measurements.

Table I

ANALYSES OF STEELS USED IN THE EXPERIMENTS

Steel	C,%	Si,%	Mn,%	P,%	S,%	Ni,%	Cr,%	Mo,%
A1	0·04	0·01	0·05	0·005	0·015	...	...	...
A2	0·06	0·31	0·35	0·011	0·010	...	...	...
A3	0·07	0·01	0·04	0·009	0·054	...	...	...
B1	0·15	...	...	...	...	...	...	...
B2	0·16	0·07	0·63	0·012	0·010	...	...	...
C1	0·27	0·21	0·60	...	...	...	...	...
C2	0·31	0·30	0·38	0·012	0·010	...	...	...
D1	0·58	0·10	0·33	...	...	...	...	...
D2	0·59	0·28	0·45	0·010	0·011	...	...	...
E1	0·70	0·15	0·66	...	...	...	...	...
E2	0·71	0·27	0·58	0·012	0·011	...	...	...
E3	0·77	0·13	0·62	...	...	...	...	...
F1	0·81	0·10	0·34	...	...	...	...	...
N37	0·12	0·30	0·55	0·011	0·013	5·20	...	...
N22	0·36	0·31	0·56	0·013	0·013	3·28	0·16	...
N23	0·32	0·28	0·65	0·011	0·010	3·29	0·87	...
N23M	0·31	0·25	0·51	0·010	0·017	3·38	0·78	0·35
CR5	0·20	0·17	0·25	0·011	0·012	0·06	3·02	...
CR4	0·51	0·20	0·38	0·014	0·013	0·06	2·96	...

CHANGE OF LATTICE SPACING IN COLD-DRAWN WIRES

Preliminary experiments were carried out to ascertain the magnitude of the change of lattice spacings in ferrite, using a Hilger iron and a 0·6% C steel. Both were cold-drawn from 0·664 in. to 0·420 in. dia. to give 60% reduction and, before drawing, were in a normalized condition. X-ray examinations were carried out on these specimens before and after drawing, using the high-angle reflections from the (211) and (220) planes as given by CrK_α and FeK_α radiations, respectively. With cold-drawn specimens the location of the X-ray beam and its angle of incidence are important ; in the present case, transverse sections were used and the X-ray beam was perpendicular to the section at its centre spot. The diameter of the diffraction rings was measured and comparisons were made between cold-worked and unworked specimens. The results, expressed as percentage change in lattice spacing, are summarized below :

	Hilger Pure Iron (60% Red.)		0·6% C Steel (60% Red.)	
	(211)	(220)	(211)	(220)
Percentage strain (compressive)	0·025	0·040	0·20	0·19

In both cases the (211) and (220) planes were in a state of compressive strain, but the magnitude of such strains was much greater for the 0·6% C steel than for the Hilger iron. Such a difference might be expected because the presence of cementite in the high-carbon steel must favour the retention of a greater lattice strain in ferrite, as will be explained later. Moreover, the stresses required for drawing would be greater in the case of the 0·6% C steel than with the Hilger iron. As shown by Wood,[30] the residual strain in the lattice of a deformed metal increases with the applied stresses.

VARIATION OF LATTICE SPACING ACROSS A WIRE SECTION

Attempts were made to find out any variations in lattice strains across the section of cold-drawn specimens. Two steels were examined, (1) *A2* (0·06% C), cold-drawn to 0·330 in. dia. to give 70% reduction, and (2) *D2* (0·59% C), cold-drawn to 0·277 in. dia.

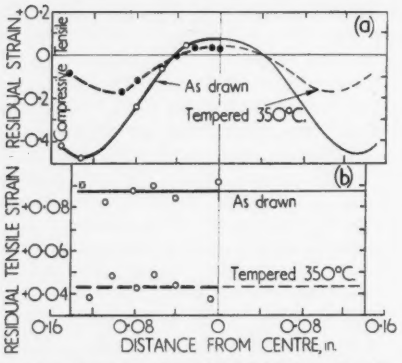


Fig. 44—Distribution of residual lattice strains ((211) spacings of ferrite) in cold-drawn steels (70% reduction, transverse direction) : (*a*) Steel *A2*, (*b*) steel *D2*

to give the same reduction. Before drawing, *A2* was normalized and *D2* was lead-patented. The X-ray measurements were made with the incident beam perpendicular to the longitudinal axis of the wire. A flat surface, $\frac{1}{8}$ in. wide, was first made along the full length of the specimen by polishing on emery papers. The surface was progressively polished and etched until the centre of the wire was reached, X-ray photographs being taken at successive stages after each etch. The diameter of the diffraction rings was compared with that of the undrawn specimen. The results, which represent the variation of the (211) spacing of ferrite across the wire section, are given in Fig. 44*a* for *A2* and in Fig. 44*b* for *D2*. The broken-line curves show similar variations after tempering the same wires at 350° C. for $\frac{1}{2}$ hr.

As shown in Fig. 44*a* there was a marked variation in the (211) spacing of ferrite along the transverse direction of the cold-drawn wire of *A2*, the strain changing from compression near the surface to tension at the centre of the section. The maximum compressive strain was at about 0·03 in. below the surface, and the maximum tensile strain was at the centre of the wire. A similar gradient of residual strains existed in the wire tempered at 350° C., as shown by the broken-line curve. In this case, the average value over the section was lower, indicating that some of the strains were removed by tempering.

With the cold-drawn specimen of the high-carbon steel *D2*, the (211) spacing of the ferrite, as measured in the transverse direction, appears to be under uniform tension across the section because the scatter of the experimental points in Fig. 44*b* was within the experimental error. This residual strain was reduced by approximately half after tempering the specimen at 350° C. for $\frac{1}{2}$ hr., as indicated by the broken-line curve in Fig. 44*b*.

Strain measurements based upon only one set of lattice spacings, as in the present case, do not give a quantitative picture of the residual stress system operative within the wires, since, in a plastically deformed metal, the change of lattice spacing caused by Heyn stress due to anisotropy of crystals differs with different planes and directions.[31] On the other hand, the effect of Heyn stress upon the change of (211) spacing in ferrite, as given by CrK_α radiation, is small, of the order of 0·001%. In view of this, the relatively large change or variation of the (211) spacing in these experiments may be mainly associated with the presence of very high body stresses resulting from non-uniform deformation across the specimen section, as is to be expected in wire-drawing. Body stresses are, of course, dependent on the mode of deformation, for which the method of working, the size of the specimen, and the hardness of the material are important. In a polycrystalline mass, body stresses, like Heyn stress, must balance themselves, and the resultant of such stresses in any one direction must be zero. Therefore, although the results based on the measurement of (211) spacing shown in Fig. 44*a* indicate, in the transverse direction, more compression than tension, the balance of stresses will be kept if the measurements of all the spacings are taken.

In a cold-drawn specimen of a high-carbon steel, the magnitude and distribution of residual strain in ferrite are expected to be different from those in a similar specimen of a low-carbon iron. Not only is a high-carbon steel considerably harder, therefore involving a higher level of applied stress in drawing, but the presence of cementite gives rise to textural stress superimposing upon the body stresses, thus modifying the internal stress system as a whole. It is considered that the apparently uniform increase in the (211) spacing of ferrite across the wire section shown in Fig. 44*b* is mainly due to the presence of textural stress resulting from mutual restraint between cementite and ferrite. Other spacings in ferrite must also be affected, but the balance of the different stresses in a given direction across the section may be mainly between cementite and ferrite. The internal strains in cementite will be considered later.

RECOVERY OF LATTICE SPACING ON TEMPERING

A small wire of the 0·59% C steel, *D2*, was used for the study of the effect of tempering upon the recovery of the lattice spacing, having been drawn from 0·25 in. to 0·158 in. to give a total reduction of 60%. X-ray patterns were taken in both the longitudinal and transverse directions on the same specimen. Similar measurements were taken after the specimen had been tempered for $\frac{1}{2}$ hr. at each successive temperature. The results, representing the recovery of the (211) spacing of ferrite, are plotted in Fig. 45. The residual strain in the as-drawn wire was approximately 0·1% compression in the longitudinal, and 0·06% tension in the transverse, direction. The 0·1% longitudinal compression was only half the value previously reported for a similar steel, also drawn 60% reduction. In making such a comparison, the size of the specimen and, what appears to be equally important, the initial treatment given to the steel, should be taken into account. In the first case, where a longitudinal compression of 0·2% was observed, the specimen was drawn for a larger diameter bar and the initial structure was a relatively coarse pearlite resulting from normalizing treatment. In the second instance (*D2*), the steel was lead-patented to give a very fine pearlite, and the wire was much smaller.

In Fig. 45 the lattice strains, as represented by the change of the (211) spacing of ferrite, were not affected to any appreciable extent when the tempering temperature was below 100° C. Above this temperature, the recovery of the lattice commenced slowly at first, but at an increasing rate as the tempering temperature was raised. The removal of such strains was complete after tempering at about 600° C.

In cold-drawn steels the (211) spacing of ferrite was in a state of compression in the direction of drawing; this is in agreement with the results of Wood,[30] who used tensile specimens. If the residual strains in other reflecting planes, although different in relative magnitude, are similar in trend to those of the (211) spacing—an assumption which would appear to be justified from Wood's findings—the recovery from such strains, as shown in Fig. 45, will then explain some of the dilatation results reported in Section I. Thus, the recovery of the ferrite grains from a compressive strain must involve an expansion in the longitudinal direction, and that from a tensile strain should produce a contraction in the transverse direction. The removal of these strains, found to be complete at about 600° C., is also in good agreement with the dilatation and density results previously described.

RECOVERY OF LINE-SHARPNESS ON TEMPERING

Low- and high-carbon steels, *A*2 and *D*2, respectively, both cold-drawn 60% reduction, were used in these experiments. With *D*2, the line-width measurements were carried out on the films taken for the study of the effect of tempering on the recovery of the lattice spacing (Fig. 45). The line width appears to be independent of the direction of the X-ray beam, because similar results were obtained from films taken on both longitudinal and transverse sections. The specimen of *A*2 was similar in size to that of *D*2; tempering was carried out at closer intervals, but the time at each successive temperature was also ½ hr. The results are shown in Figs. 46*a* and *b* for *A*2 and *D*2, respectively.

X-ray line-broadening is usually represented by 'half-width' measurements. In Fig. 46, however, the values are based upon the width of the CrK_α Fe (211) doublets at two-fifths of the maximum intensity, because, with the fine focusing pinhole system used, the doublets obtained on the specimens tempered at 500° C. and above were well resolved, and the line width corresponding to the half maximum intensity included the gap separating the α_1 and α_2 components. Since these experiments were extended to above the recrystallization temperature, the width of the lines at two-fifths of their maximum intensity was adopted.

The line-broadening associated with the cold-drawn low-carbon steel, *A*2 (Fig. 46*a*), diminishes with increasing tempering temperature, and the shape of the curve bears a close relationship to the hardness/tempering-temperature curve in Section I (Fig. 2*a*). With the high-carbon steel, *D*2, however, this relationship did not exist. For example, the hardness of a cold-drawn high-carbon steel invariably increases on tempering, and generally reaches a maximum at about 300° C., whilst the width of the X-ray diffraction line, as shown in Fig. 46*b*, decreases rapidly just above 100° C. The line-broadening brought about by cold-drawing appears to be more marked in the high-carbon than in the low-carbon steel.

RELATION BETWEEN LINE-BROADENING AND DEGREE OF COLD-WORK

To find the relation between X-ray line-broadening and the degree of cold-work, *A*3, an ingot iron which appeared to contain some oxide inclusions, and *D*2 were used (the stock of *A*2 had been exhausted). Both *A*3 and *D*2 were normalized before cold-drawing. The results on the transverse sections are given in Fig. 47. The values represent the line-widths at two-fifths of their maximum intensities.

As might be expected, the line-broadening increased

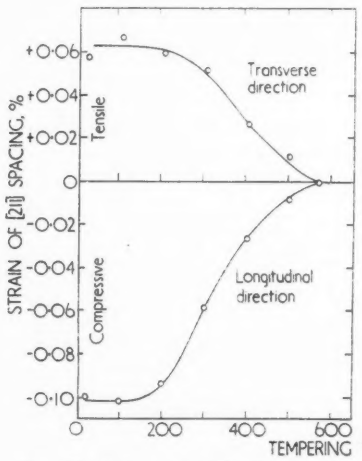


Fig. 45—Recovery of ferrite lattice strains ((211) spacings) in steel *D*2 (60% reduction) on tempering

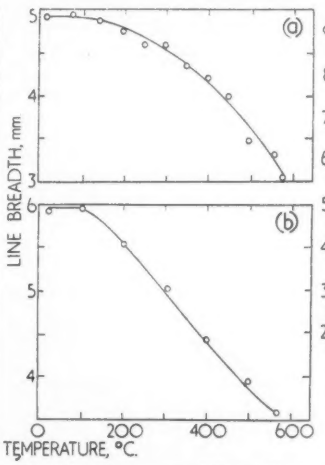


Fig. 46—Recovery of X-ray line sharpness in cold-drawn steels (60% reduction) on tempering: (*a*) Steel *A*2, (*b*) Steel *D*2

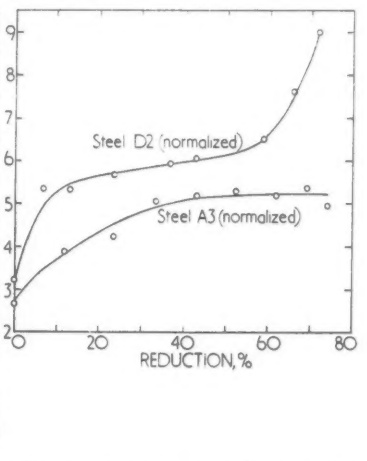


Fig. 47—Variation of X-ray line breadth with percentage reduction by cold-drawing

with the degree of drawing for both steels and, for a given reduction, this increase was greater for the high-carbon steel *D*2 than for the ingot iron *A*3. The most significant feature of these results is that the shape of the curves for *D*2 and *A*3 is similar to their respective hardness curves given in Section I. Thus, with the ingot iron, there was no abrupt increase towards high reductions in either the hardness or the X-ray line width, but both the hardness and the line-broadening of the high-carbon steel *D*2 increased markedly beyond about 60% reduction.

DISCUSSION OF RESULTS

The presence of residual lattice strains in cold-worked metals associated with Heyn stress due to anisotropy of crystal grains has been widely demonstrated by previous workers.[30,31] In the case of the (211) spacing of ferrite, residual strains associated with Heyn stress are known to be small. The relatively large change in the X-ray ring diameter observed in the present experiments has been attributed to the effect of body stresses. In wire-drawing, the surface of the specimen is more severely deformed than the centre when passing through the die. On releasing the pulling force, the surface will be thrown into compression and the centre will be under residual tension in the transverse direction. Such a variation of body stresses is in keeping with the results given in Fig. 44*a*.

With a high-carbon steel, the presence of cementite causes complications. Apart from the body stresses mentioned above, the presence of cementite must give rise to textural stress, the effect of which upon lattice spacings of ferrite may reach a macroscopic scale for the following reasons. Supposing that the yield stress of cementite is greater than that of ferrite, then, on cold-working, some of the cementite may be only elastically deformed, whilst the surrounding ferrite has undergone plastic yielding. Therefore, after the applied stress is removed, the ferrite grains will be left in a state of compression with the cementite under tension in the drawing direction. In the transverse direction, the signs of the strains will be reversed. The magnitude of such strains will depend to some extent upon the amount and the state of division of the cementite present, in other words, on the carbon content and the intial treatment of the steel. The release of such strains on heating will result in a residual expansion in the longitudinal direction and a contraction in the transverse direction of the wire. This is in agreement with the dilatation results previously reported.

It is generally accepted that the X-ray line-broadening in cold-worked metals is associated with lattice distortion and small crystallite sizes, and these two factors are believed to be the cause of increase in hardness. The results for *A*3, on cold-drawing, and for *A*2, when cold-drawn followed by tempering, appear to agree with this view, since the effects observed are similar to those obtained with other metals. With the high-carbon steel, *D*2, however, although, in the as-drawn condition, the X-ray line width follows closely with the hardness, the cause of the rapid increase in both towards high reductions (above 60%) is not clearly understood. Further, the fact that the hardness of a cold-drawn high-carbon steel increases on tempering up to 300° C., whilst the X-ray line-broadening decreases, requires careful consideration. These anomalies may be connected with certain changes taking place in the cementite and the removal of macro-strains in ferrite, as will be discussed in conjunction with the results reported in other Sections.

Section IV—EFFECT OF HIGH-SPEED DEFORMATION ON STEEL

With L. Bourne, B.Met.

SYNOPSIS

The effect of rapid deformation on steel, by means of a dynamic load impact, has been investigated, and the results confirm those of previous workers, *viz.*, that the deformation is extremely localized, giving rise to the formation of a white band. X-ray examination shows this band to contain austenite and martensite.

WHILST no constitutional changes have been found when steel is cold-worked by normal processes of deformation, such as drawing or rolling, or tensile elongation or compression, such changes are possible if the deformation is conducted at a very high speed. Trent[12] showed that a light-etching white layer was produced in a steel wire subjected to a rapid blow by a hammer. He contended that the white layer was martensitic, and his microscopic evidence was later substantiated by hardness measurements. In the discussion of Trent's paper, one of the present authors pointed out that the white layer also contained some austenite. The present investigation was directed primarily to examine the real nature of the white layers produced in steel by rapid deformation.

Deformation of the Specimens

In the present experiments the specimens were 0·3 × 0·3 × 0·75 in. Each specimen was placed with one of its rectangular faces flat on a heavy steel anvil and was deformed by being struck with an 8-lb. weight falling from a height of 24 ft. The weight was released suddenly and was guided towards the specimen along two slide wires. A single blow reduced the thickness of the specimen by about 50%. A rough estimation of the speed indicated that the deformation must have occurred within a short period of the order of 10^{-3} sec. Owing to the many complications, it has not been possible to give even an approximation of the amount of energy put into the deformed specimen.

The experiments were first carried out on a lead-patented 0·70% C steel *E*1, which had a very fine pearlite structure. When this steel was subjected to the deformation the specimen was usually split into two pieces along a plane of maximum shear, but in certain cases the fracture did not extend across the whole section. Micro-examination of such

specimens showed that a white layer was present at the fractured face. If the specimen had not been completely split, the white layer extended from the fractured face to a region slightly beyond it. To the naked eye, the fractured face showed shining and bright areas which could be identified with the white layers when examined under the microscope. Figure 48 shows one of the fractured faces.

X-RAY EXAMINATION

Using a 10-cm. glancing-incidence camera and cobalt radiation, X-ray examinations were carried out on the bright areas of the fractured face, and one of the patterns obtained is shown in Fig. 49*b*. For comparison, a similar pattern obtained on an undeformed specimen is given in Fig. 49*a*. This specimen showed the presence of ferritic phase only. In Fig. 49*b*, however, there are at least three lines in addition to those corresponding to the ferritic phase and these could be fitted in with the (111), (200), and (220) planes, respectively, in austenite. This suggests that the white layer observed on the fractured face contained a small amount of austenite.

As the specimen was hot after deformation, it was thought that the amount of austenite retained might be increased if the extraction of heat from the specimen could be accelerated by applying external cooling. Another specimen was immersed in a pool of water spread over the top of the steel anvil when the blow was struck. The X-ray pattern obtained on the fractured face of this specimen, Fig. 49*c*, shows four extra lines which can be fitted in with the austenite pattern, the additional one being the diffraction from the (311) plane of the gamma lattice. It appears that, with water-cooling, the amount of austenite retained in the white layers was slightly greater.

Similar experiments were carried out on a nickel–chromium steel containing 2% Ni, 3% Cr, and 0·35% C. It was thought that, since the presence of alloying elements in steel promotes the retention of austenite, the Ni–Cr steel might enable even more clear evidence to be obtained with regard to austenite formation on high-speed deformation. Before deformation, the steel was annealed and slowly cooled from above the Ac_3 temperature. This treatment did not give the maximum softness of the steel until it was again annealed at a subcritical temperature of 600–650° C. The resulting structure was a fine pearlite with signs of spheroidization. The blow did not fracture or split the specimen although white layers were present. Figure 50*a* is a typical photograph showing the white layers. Also in the photograph is a row of micro-hardness impressions, and the corresponding hardness values are plotted in Fig. 50*b*. The hardness of the white layers was of the order of 650–700 V.P.N., as compared with about 320 V.P.N. for the background structure. Thus the deformation was extremely localized ; this is further borne out by the fact that the hardness of the specimen was practically constant up to the very edge of the white layers. The high hardness suggests that the white layers were mainly martensitic, as shown by Trent.[12]

With an unsplit specimen it was more difficult to detect any austenite in the white layers. An X-ray beam could, of course, be directed to the spots on the micro-section where the white layers are situated, but the area of the white layers could be only a very small fraction of the total area covered by the beam. Also, the percentage of austenite in the white layers would be relatively small and in many cases barely detectable. Therefore the section was prepared so that one whole white layer could be exposed to the X-ray beam. The procedure adopted was as follows.

After locating the exact position of the white layers by micro-examination, the micro-specimen was sectioned along a plane parallel to the stratum of one of the white layers to be X-rayed, the specimen being mounted in a block of bakelite. (It was considered that heating the specimen to about 100° C. would not affect austenite to any appreciable extent.) The sectioned surface was polished down to the white layer, care being taken to avoid excessive heating. The white layer was finally exposed by etching. Figure 51 shows the section prepared in this way ; the exposed white layer occupies nearly half the area of the section. The results of X-ray examinations on this white layer, both before and after tempering, are given in Fig. 52 (*b* to *f*). The pattern for an unstrained specimen of the same steel is included (Fig. 52*a*) for comparision.

Figure 52 shows that the unstrained specimen gave only an alpha pattern (*a*). On the other hand, the pattern for the white layer (*b*) indicates the presence of austenite in addition to the ferritic phase. The five diffraction lines, (111), (200), (220), (311), and (222), which are characteristic of the austenitic lattice with Co radiation can be seen. After tempering the specimen at 250° C. for 1 hr., the austenite lines were fainter (*c*). With higher temperatures, such as 350° C. (*d*) and 450° C. (*e*), the intensity of the austenite lines decreased further until they had completely vanished after tempering for 1 hr. at 500° C. (*f*). These experiments indicate that some of the austenite retained in the white layers produced in the Ni–Cr steel was quite stable.

MICRO-EXAMINATION

Micro-examinations were also carried out, and the corresponding photographs of similar specimens are shown in Fig. 53. The structure of the unstrained specimen was a fine pearlite, spheroidized to some extent in view of the subcritical annealing treatment (Fig. 53*a*). The white layer produced in the deformed specimen is shown in Fig. 53*b* ; the demarcation between the white layer and the matrix is not sharp, and some carbide particles appear to be in a state of incipient solution or precipitation. On tempering, the precipitation of the carbide particles took place in the white layer, usually at first near the edges. Hence, as the tempering temperature was increased, the white layer became progressively narrower. This is clearly shown in Figs. 53*c*, *d*, and *e*, representing the same white layer after tempering for 1 hr. at 250°, 350°, and 450° C., respectively. In Fig. 53*f*, after tempering the specimen at 500° C. for 1 hr., the precipitation of carbide from the white layer was complete. In general, the micro results agree well with the X-ray finding in Fig. 52.

DISCUSSION

Micro-hardness determinations were made on the specimen after each tempering. The hardness of the white layer increased after tempering and the maximum increment, about 50 points, was obtained at 300° C. The hardness of the matrix near the white layer was also measured and a similar increase was obtained. Whilst the decomposition of austenite might be responsible for the increase in the tempering hardness of the white layer, it is difficult to explain the secondary-hardening phenomenon observed in the adjacent matrix because no change was visible either under the microscope or by X-ray examination.

The fact that, on tempering, the decomposition of austenite and the accompanying precipitation of carbide usually proceeded from the edge of the white layer may be significant. If the white layer was formed as a result of localized heat produced during deformation, it would appear that the centre of the layer would attain a higher temperature than its edges. Therefore, the solution of the carbon and carbide-forming elements would be more complete at the centre of the layer than near its edges. In other words, there might be a concentration gradient with respect to the solution of carbon in austenite or martensite across the white layer, the carbon concentration being the highest at the centre. If this assumption is correct, it may then be expected that the austenite or martensite at the centre of the white layer will be relatively more stable and, therefore, will be the last to decompose on tempering.

The contention that the formation of austenite and martensite in steel on rapid deformation, such as in the present experiments, is due to localized heat, has much supporting evidence. For example, immediately after the deformation, the specimen was hot. This may be connected with the dissipation of heat from the white layer after it has been formed. Moreover, martensitic layers similar to those obtained in the present experiments can be produced by surface friction. From a theoretical point of view, Zener and Holloman[32] have carried out similar experiments under what they called adiabatic conditions. They produced martensitic layers in carbon steel and their calculations show that a shear factor of 5 could give rise to a temperature of the order of 1000° C. within the narrow region, as represented by the dimensions of the white layers produced. The energy put into their specimen, as Zener and Holloman indicated, would probably give a shear factor of 100.

Whereas austenite has been shown to be present in the white layers, there appears to be no clear evidence of tetragonal martensite, as indicated by the X-ray results in Figs. 49 and 52. The white layers would be expected to contain no less than 90% of martensite because of the high hardness values, and therefore the martensite lines should stand out much more clearly than the austenite lines. The results shown are the reverse. The only possible explanation is that the martensite in the white layer might be mainly in a tempered condition. This would seem to be reasonable because tempering at 100–150° C. alters very appreciably the tetragonality of the martensite through incipient formation of carbide, without affecting the hardness of the specimen. Austenite, on the other hand, is more stable and will not decompose to any marked extent until the temperature is well above 200° C.

CONCLUSION

The results given in this Section justify the conclusion that, under adiabatic conditions, as produced by very rapid rates of deformation, austenite and martensite may form in cold-worked steel as a result of localized heat generated along planes of maximum shear. Owing to the rapid conduction of heat through the matrix, some of the austenite may be retained after deformation.

Section V—AN X-RAY INVESTIGATION OF STRUCTURAL CHANGES IN STEEL DUE TO COLD-WORKING

By D. V. Wilson, M.A., F.R.I.C.

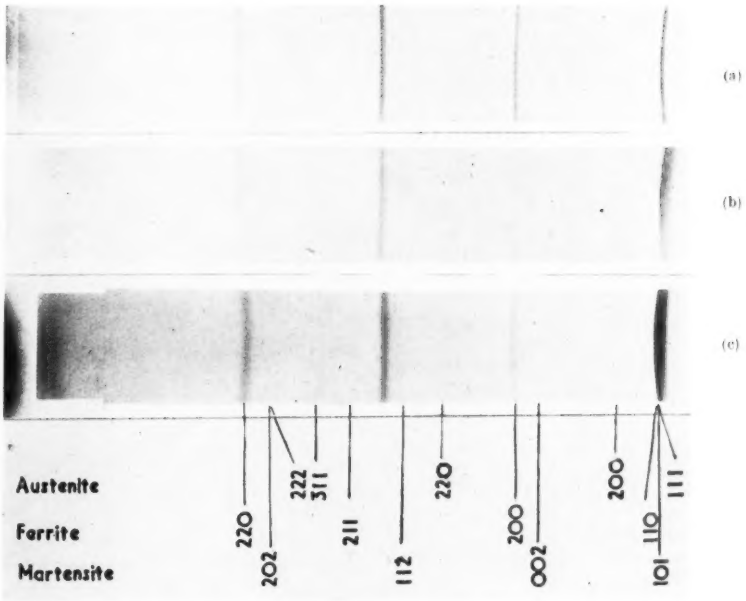
SYNOPSIS

X-ray examinations on high-carbon and alloy steels after cold-working by compression have failed to reveal the presence of austenite in unfractured test-pieces. It is shown, however, that austenite may be formed on the surface of shear fractures. An X-ray investigation of the influence of severe cold-working on cementite in steel has been made, and evidence of large residual strains in such cementite, together with some tendency towards preferred orientation, has been found.

THE work described in this Section comprises an X-ray crystallographic examination carried out to seek evidence of certain constitutional changes, which, it has been suggested, may accompany the cold-working of steel. Two hypotheses, in particular, have been considered: firstly, that carbon is taken into solid solution by the iron during cold-working and that this is probably brought about by the formation of austenite, at least temporarily, in the neighbourhood of the slip planes of the ferrite, due to local temperature and pressure effects during plastic deformation. The second hypothesis, which has been advanced more recently, principally as a result of magnetic and electrical resistivity investigations, suggests that some form of structural change within the cementite itself may be brought about by cold-working.

The present investigation has involved two series of experiments, designed to seek direct evidence of transformations of the two types just mentioned.

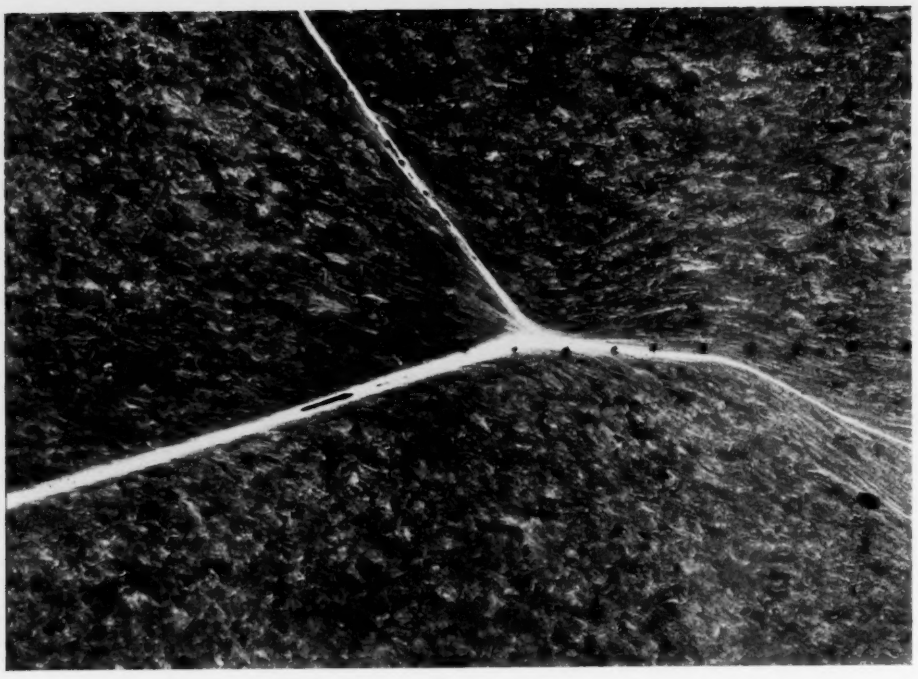
Fig. 48—Fracture of a 0·7% C steel (*E*1) produced by rapid deformation × 3



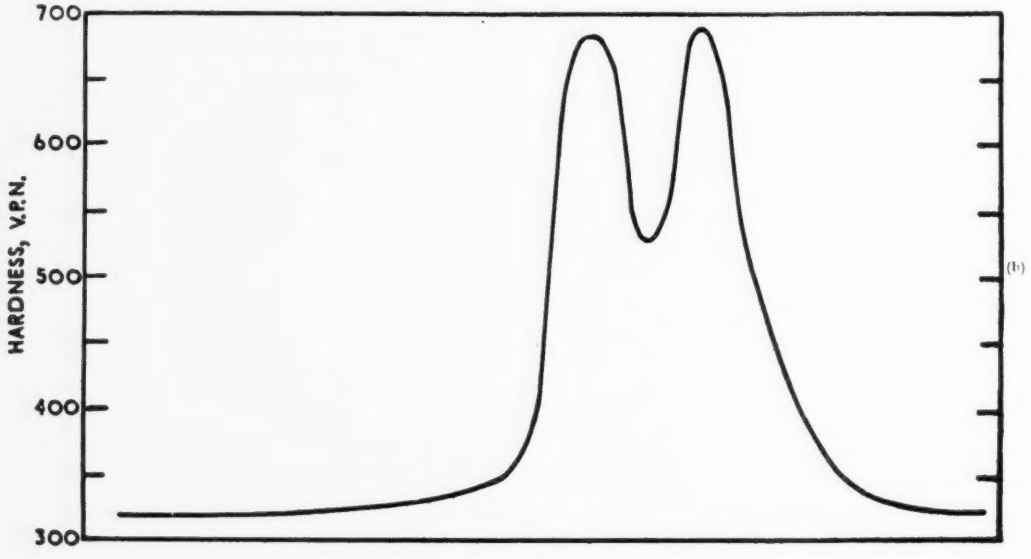
(*a*) Undeformed specimen
(*b*) Fractured surface (deformation without water-cooling)
(*c*) Fractured surface (deformation with water-cooling)

Fig. 49—X-ray patterns obtained on a 0·70% C steel, *E*1 (Co radiation)

[*Andrew and others*
[*To face p.* 376



(a)



(b)

Fig. 50—(*a*) **Micrograph of a Ni–Cr steel (2% Ni, 3% Cr, 0·35% C), showing white layer × 100 (*b*) The corresponding hardness curve**

Fig. 51—Specimen of a Ni–Cr steel, polished to reveal the white layer × 2

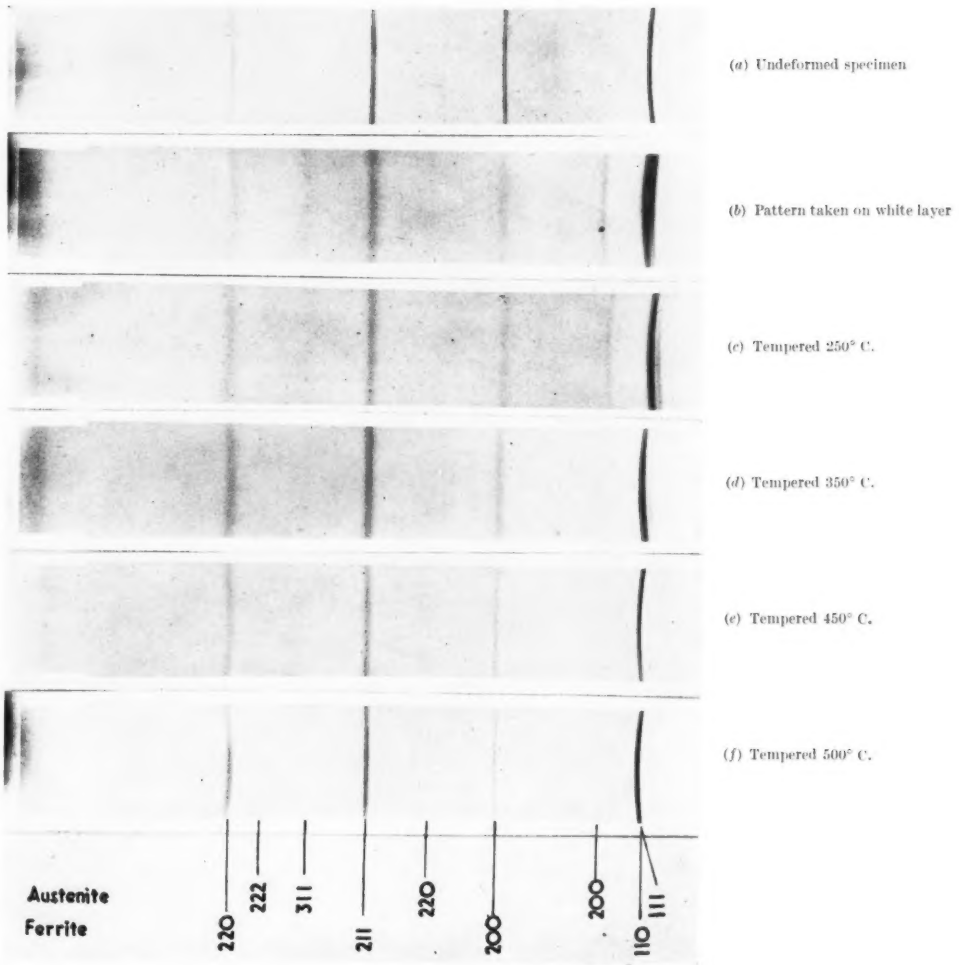
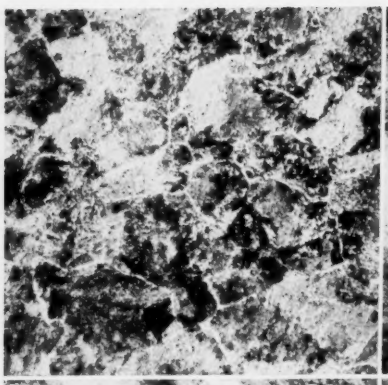
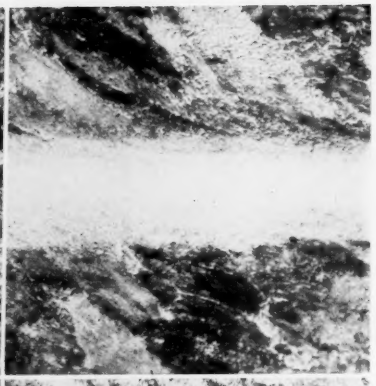


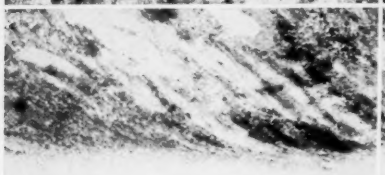
Fig. 52—X-ray patterns obtained on a Ni–Cr steel. Co radiation

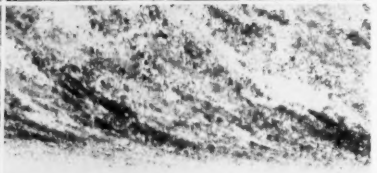
(*a*) Undeformed



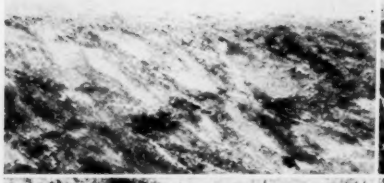
(*b*) White layer



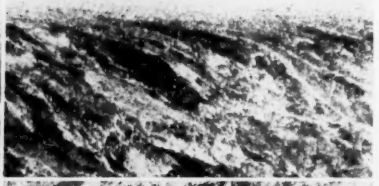


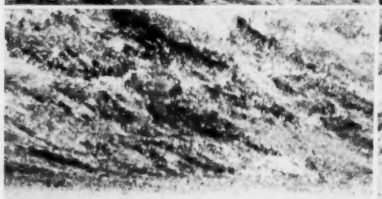


(*c*) Tempered 250° C.

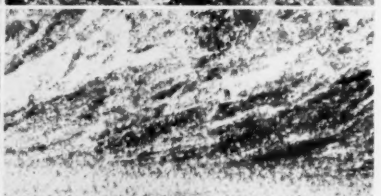


(*d*) Tempered 350° C.





(*e*) Tempered 450° C.



(*f*) Tempered 500° C.

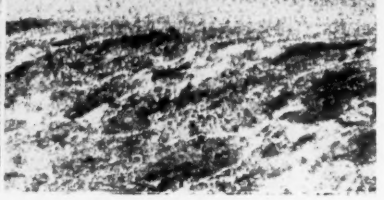
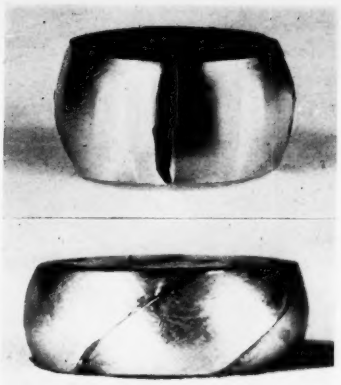


Fig. 53—Photomicrographs corresponding to X-ray results shown in Fig. 52. Nickel-chromium steel × **400**



(a)

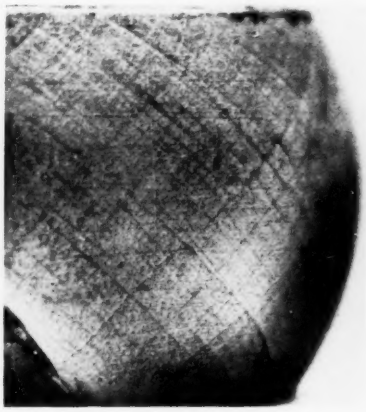
(b)

Fig. 54—Fractures in compression pieces. (*a*) Vertical fracture, (*b*) 45° fracture

Fig. 55—Micrograph of 45° shear fracture in high-carbon, high-chromium steel. Etched with 5% nital × 100

(a)

(b)



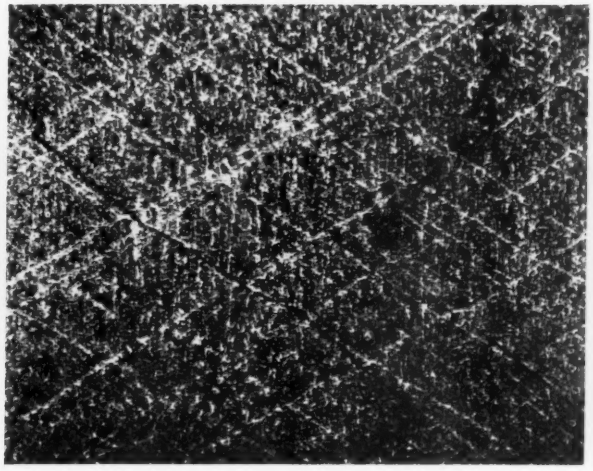
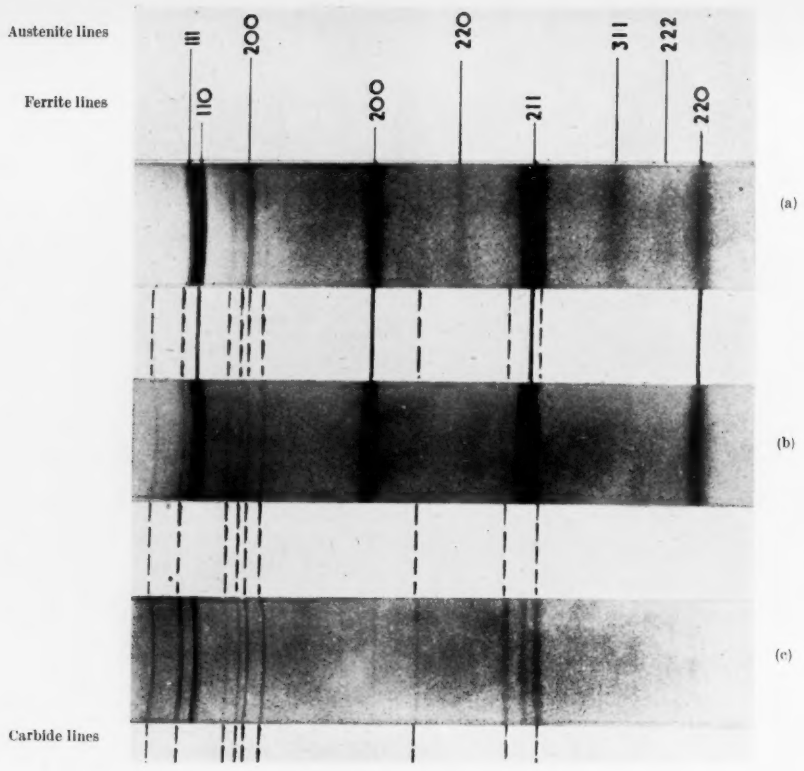


Fig. 56—(*a*) Surface markings on compression piece × 10 (*b*) Shear planes in section just below surface of specimen shown in (*a*). Vertical compression. Etched with 2% nital × 35



(*a*) 45° Shear fracture of heat-treated 1% C, 15% Cr compression piece
(*b*) Vertical fracture in the same sample as (*a*)
(c) Chromium carbide $(Fe, Cr)_7 C_3$ separated from the steel shown in (*a*) and (*b*)

Fig. 57—X-ray diffraction patterns illustrating the formation of austenite on 45° fractures of a compression piece (Co Kα radiation

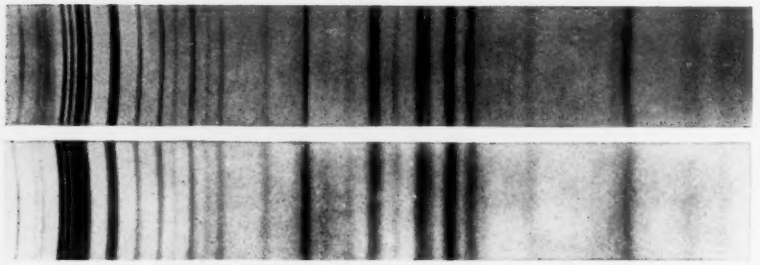


Fig. 58—Carbides separated from a 1·2% steel C (Co Kα radiation)

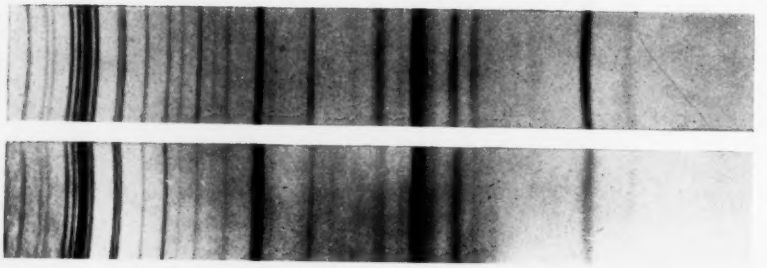
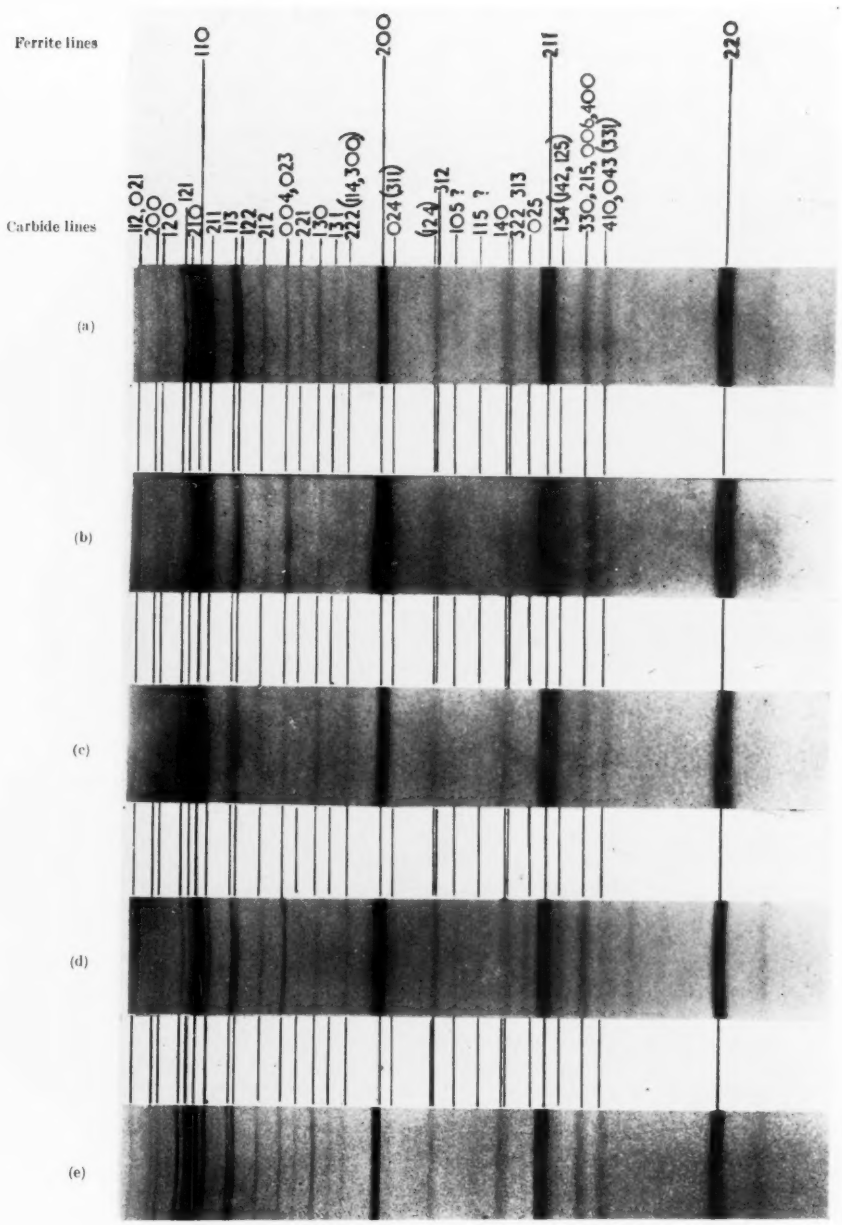
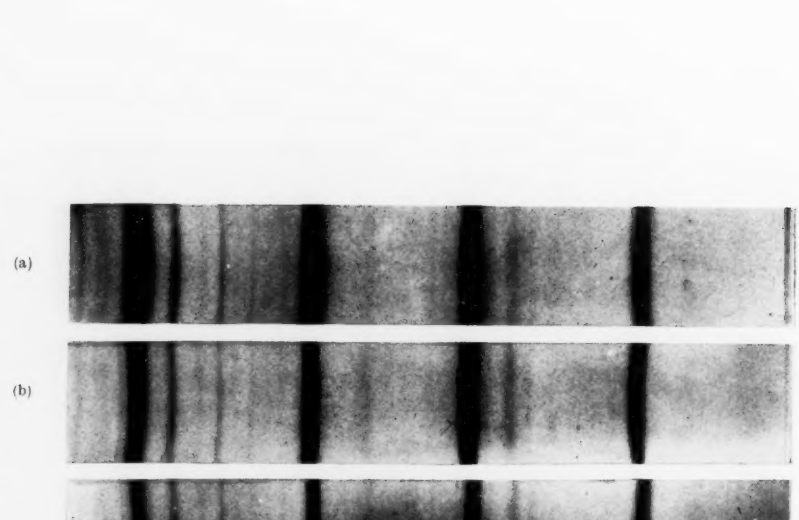


Fig. 59—Carbides present in a 1·2% C steel. Etched electrolytically



(*a*) Undeformed
(*b*) Cold-worked, transverse section
(*c*) Cold-worked, longitudinal section
(*d*) Worked and annealed at 600° C., transverse section
(*e*) Worked and annealed at 600° C., longitudinal section

Fig. 60—Influence of cold-working and subsequent annealing of carbide diffraction pattern of 1·2% C steel (unetched sections)



(*a*) Untempered
(*b*) 250° C.
(*c*) 320° C.
(*d*) 400° C.
(*e*) 480° C.
(*f*) 600° C.

Fig. 61—Influence of tempering temperature on diffraction pattern of heavily deformed (reduced 90%) 1·2% C steel. Co Kα radiation, glancing-angle camera. Specimens unetched

EXPERIMENTAL METHOD

Since it was desired to investigate relatively hard and brittle materials, cold-working was carried out by compression, between lubricated and polished hard steel pads, on a hydraulic testing machine. The specimens were machined and polished to give cylinders 0·65 in. long by 0·40 in. dia. They were then heat-treated and, where necessary, quenched, in an atmosphere of dry nitrogen to avoid scaling. After hand-polishing, the specimens were compressed to the required degree of deformation. The rate of straining being of the order of 4% per minute, deformation was completed without any sensible rise in temperature. After deformation, the surfaces of the specimens selected for examination were lightly polished on wet emery paper to 000 grade and, when necessary, were etched in 2% nitric acid.

X-ray examinations were made with a 10-cm. dia. Debye-Scherrer glancing-angle camera. Both cobalt and chromium K_α radiations have been used but, for the present work, cobalt has proved more useful. An appropriate β-filter was employed on the incident X-ray beam and an aluminium foil screen was interposed between specimen and film.

The results are described in two parts, firstly the examination for retained austenite, and secondly the investigation of the influence of cold-work upon carbides.

FORMATION OF AUSTENITE DURING COLD-WORKING

Previous investigations on soft plain carbon steels deformed at ordinary rates of straining have given no X-ray diffraction evidence of the formation of austenite during cold-working. Although, in general, the X-ray diffraction method is necessary to establish the precise nature of a structural transformation, X-ray patterns are rarely sensitive in showing the presence of a small proportion of a second phase. Moreover, the ordinary sensitivity is reduced if the material sought is present in the form of extremely small or highly strained particles—as is almost certain to be the case with a new constituent produced as a result of cold-working.

Therefore the present investigation has been extended to materials judged more favourable for the formation of austenite or martensite. Three steels, of the following compositions, have been employed :

	Steel F2	Steel 3NS	15% Cr Steel
Carbon, %	0·88	0·38	1·00
Silicon, %	0·04	0·25	0·55
Manganese, %	0·26	0·53	0·69
Sulphur, %	...	0·011	0·029
Phosphorus, %	...	0·006	0·020
Nickel, %	...	3·43	...
Chromium, %	...	0·12	14·9

These steels provide a basis for the investigation of materials having marked differences in their carbide and solid solution phases. In addition to the differing compositions, the influence of variations in microstructure, due to previous heat-treatment, has also been considered.

If austenite may be formed and if some carbide solution can occur during plastic deformation, then it seems reasonable to suppose that the retention of such austenite will be most easily achieved in high-carbon and high-alloy steels. Moreover, in a given steel, it seems likely that carbide solution would most easily occur in a refined structure, such as tempered martensite, owing to the very fine state of division of the carbides in this structure and the relatively large amount of energy dissipated during the working process. Particular attention has therefore been given to quenched and tempered specimens.

The quenching temperatures were 800° C. for F2 and 3NS, and 1000° C. for the 15% Cr steel. In each case specimens were prepared with differing tempering treatments. Tempering temperatures ranged from 300° C. upwards for steel F2, 370° C. upwards for 3NS, and 500° C. upwards for the 15% Cr steel. In the case of the 15% Cr steel, two separate periods of 1 hr., with intermediate cooling to room temperature, were employed. These minimum tempering temperatures were adopted mainly to ensure that, before cold-working, the steels were freed from any detectable trace of austenite retained after the quenching treatments. This was confirmed by X-ray examination. After tempering at the minimum tempering temperatures the hardness was approximately 600 V.P.N. for steel F2, 470 V.P.N. for steel 3NS, and 630 V.P.N. for the 15% Cr steel. These conditions corresponded to the finest possible dispersion of the carbides, consistent with a reasonable certainty that there should be no retained austenite in the specimens before working. Specimens with hardness values ranging from the values mentioned down to those corresponding to the fully softened state were prepared from each steel.

Generally, the specimens were compressed within the range 30–60% reduction in height, and were then subjected to X-ray examination.

No X-ray evidence of the formation of austenite or martensite as a result of cold-working was found, except in certain specimens which fractured during deformation.

Examination of Unfractured Specimens

Since results were uniformly negative it will be sufficient to indicate the ground covered in these first experiments. In view of the negative results obtained with the softer specimens, particular attention was given to the hardest specimens of each steel and to the heaviest degrees of deformation which could be obtained without fracture. (The limit of reduction of height, in the hardest condition investigated, was about 40% for steel F2, 30% for the 15% Cr steel, and 55% for 3NS.) In general, X-ray examinations were made on surfaces both parallel and perpendicular to the axis of compression, and, for the hardest specimens of each steel, also at 45° to the compression axis.

In all cases the only changes observed were those associated with internal strains in ferrite.

Examination of Fractured Specimens

In attempting high degrees of deformation in the harder compression pieces, a number of specimens were cracked or fractured. The fractured surfaces

showed certain interesting features and were examined further.

Generally, the specimens failed in compression by the formation of well-defined cracks, either parallel to, or at 45° to, the axis of the specimen. These cracks are illustrated in Fig. 54. In Fig. 54*a* the trace of a 45° crack may be seen, in addition to the vertical crack.

Consideration of a number of samples suggests that the vertical type of fracture is liable to occur in hyper-eutectoid steels in which strings of carbide particles, drawn out parallel to the axis of the specimen in prior hot-rolling, give longitudinally disposed stress-raisers at the cylindrical surface of the specimen. In the absence of such directional stress-raisers, the more general 45° shear fracture may occur in both hypo- and hyper-eutectoid steels, provided that they are sufficiently hard and are severely cold-worked.

The surface textures of the two types of fracture were notably different. The 45° shear fractures were invariably smooth and shiny, whilst the vertical fractures were of a mat and generally rough appearance. The 45° fractures were very resistant to etching in nital and similar solutions, whilst the vertical fractures showed normal dark-etching properties. The former characteristic is illustrated in Fig. 55, a micrograph of a 45° shear fracture in a high-carbon high-chromium steel (15%Cr steel hardened at 1000° C. and tempered at 550° C.). The fracture surface was lightly polished before etching in a 5% nital solution. The lower part of the micrograph shows an area in which the fracture surface has been polished away to expose the underlying material, whilst the upper area, defined by the scratches on the original fracture, has been little affected by the polishing. This specimen reveals the presence of an extremely thin layer of material on the fracture surface, which is very much more resistant to etching than is the material of the specimen as a whole. The 45° fracture surfaces of this steel retained their light-etching properties after tempering at temperatures up to about 450° C.

These observations suggested the possible presence of austenite on the 45° fracture surfaces and were followed by an X-ray examination. It was possible to detect a face-centred cubic phase of a lattice parameter corresponding to γ-iron on the light-etching 45° fracture surfaces, although there was no evidence of such a phase in the material before compression or even on the vertical fracture surfaces of the same specimen.

Figure 57 shows photographs of X-ray films illustrating the presence of austenite on the 45° shear fracture of a high-carbon high-chromium (15%) steel specimen. The pattern shown in (*a*) was given by the light-etching 45° fracture, whilst (*b*) was given by a vertical fracture in the same specimen. Some chromium carbide $(Fe,Cr)_7C_3$ lines appear in the films ; these may be identified by reference to the diffraction pattern of the separated carbide obtained from the same steel (*c*). The film given by the 45° fracture surface shows, in addition to the ferrite and carbide lines, five faint and notably diffuse lines corresponding to the austenite structure. These are absent from the pattern obtained from a vertical fracture of the same specimen. The photograph corresponding to the specimen before compression has not been included as it was very similar to that given by the vertical fracture, except that the carbide lines were rather less prominent.

Traces of austenite are probably also present on some 45° fractures of the hardened and tempered plain carbon steel, but traces of only the first two lines of the face-centred cubic structure were detected.

As a result of these observations it was concluded that austenite may be formed on the shear fracture surfaces of steel compression pieces, possibly as a result of the momentary development of high temperatures, due to friction caused by the sudden relative movement of the two surfaces during the fracture process. Although compression was carried out very slowly, evidence of rapid movement at fracture, due to the release of the elastic strain energy of the machine, was frequently observed. In this respect, the present experiments may bear resemblance to those described in Section IV.

An attempt has been made to extend this work a little further. It appears that fracture on 45° shear planes in compressive straining may be preceded by localization of deformation on such planes near the edge of the specimen. As a result of this localized deformation, strain lines, rather similar in appearance to stretcher-strain markings, may be seen to develop on the free cylindrical surfaces of some specimens when deformed to near fracture strain. An interesting feature of this condition is that, on a polished section of a surface showing these markings, the planes on which deformation has been localized appear to be slightly more resistant to etching in dilute nital solutions than is the material as a whole.

Figure 56*a* shows the strain lines on the surface of a compressed specimen, and Fig. 56*b* shows a particularly clear example of the light-etching tendency of the corresponding shear planes in a section just below the surface of the same specimen. This specimen was a eutectoid plain carbon steel hardened at 800° C. and tempered at 370° C. before compression. It was etched in 2% nital for 20 sec. The relatively uniform dark-etching matrix seemed particularly suited to showing up what is, in fact, a small difference in etching properties.

This localized deformation on shear planes may occur during slow deformation. Certainly it has been observed in the absence of any sudden drop in load, corresponding to fracture during compression. By polishing, an area was obtained, coincident with the plane of a representative light-etching band, large enough for X-ray examination. Polishing was carried out entirely by hand on wet emery paper, but X-ray examination gave no evidence of the presence of either austenite or martensite in the light-etching planes of the eutectoid plain carbon steel. Moreover, tempering experiments suggested that the light-etching tendency is retained after tempering at least up to 350° C. Micro-hardness tests showed the bands to be slightly harder than the material as a whole.

At present the nature of the light-etching planes is unknown, and it is hoped to carry out further experiments in this field.

INFLUENCE OF PLASTIC DEFORMATION ON THE CARBIDES IN STEEL

The object of this second X-ray crystallographic investigation was to obtain evidence of the influence of cold-work on the structure of the carbides in the deformed steel. Since observations on separated carbides are of limited value for this purpose, it was necessary to examine the carbides as present in the steels. Accordingly, relatively high-carbon steels in the annealed condition, which give reasonably clear X-ray diffraction patterns of the carbide phases, were used. All the observations described in this section were made on a plain carbon steel of the following analysis :

	%		%
Carbon	1·26	Manganese	0·31
Silicon	0·27	Nickel	0·05
Sulphur	0·012	Chromium	Nil
Phosphorus	0·023		

Before working, the steel was quenched from above the critical range and was then spheroidized at 650° C. for 8 hr., giving a microstructure containing rounded carbide particles. As in the previous experiments, the specimens were worked by compression, and reductions up to 95% were attained.

For X-ray examination a 10-cm. glancing-angle camera, with filtered cobalt radiation, was again used. During exposure an aluminium foil screen was placed in front of the films, which were developed to give high contrast. The incident X-ray beam made an angle of 38° with the surface under examination.

Experimental Results

The first examinations were made on carbides separated electrolytically from worked and unworked specimens. Clear diffraction patterns were obtained from the separated carbides. Those given by the 1·2% carbon steel are shown in Fig. 58, in which pattern (*a*) was given by carbide separated from an unworked specimen and (*b*) from a specimen compressed to 90% reduction in height. The only obvious differences between the two patterns were a broadening and a reduction in maximum intensity of the lines given by the carbide from the deformed steel. In the original films it may be seen that the maximum grain size of the undeformed carbide was sufficiently large to give individual spots in the diffraction rings. The lines given by the carbide from the deformed specimen were perfectly smooth. Evidently the grain size of the carbide particles had been reduced, possibly during cold-working.

These results could not be regarded as satisfactory, particularly because some decomposition of the carbides during separation could not be avoided, the carbides in the deformed specimens appearing to be affected to the greater extent. Clearly, in the event of the cementite being partially transformed to a new carbide phase in the cold-worked specimen, such decomposition could be selective.

Next, an examination was made of the carbides as present in the steel. Several specimens, which had been compressed within the range 0–95% reduction in height, were lightly hand-polished on surfaces perpendicular to the compression axis. Wet emery paper to 000 grade was used and the specimens were not etched before examination. Although the carbide diffraction patterns obtained were faint and somewhat obscured by the heavy background, they were sufficiently clear to suggest the occurrence of a significant modification as a result of cold-working the steel.

Attempts were made to improve the clarity of the carbide patterns by etching away the ferrite from the surfaces used in examination. The best results were obtained by electrolytic etching (using a nearly neutral dilute ferric chloride electrolyte and a current density of the order of 5 m.amp./sq. cm. for about 1½ hr.). Ferrite was removed from the surfaces to be used in X-ray examination without apparent decomposition of the carbide, and very clear carbide diffraction patterns were obtained from etched surfaces of both the worked and the unworked specimens. Examples are shown in Fig. 59. After etching, the changes in the pattern resulting from cold-working were very much less obvious than those of the unetched specimens. The only noteworthy difference in the reproductions is a change in the relative intensities of certain lines.

It was concluded that a complete picture of the condition of the carbide in a cold-worked steel can be obtained only by examination of the carbide whilst embedded in the ferrite matrix.

Figures 60*a* and *b* show the patterns given by unetched sections of undeformed and heavily worked (90% reduction) specimens of the 1·2% carbon steel. The section giving pattern (*b*) was perpendicular to the compression axis. The films, having an exceptionally wide range of line intensities, lose much detail in printing. In particular, the broadening of the over-exposed ferrite lines is considerably exaggerated. Nevertheless, the photographs illustrate some of the principal features.

As might be expected, the lines in the pattern of the cold-worked specimen are generally more diffuse and less intense than the corresponding lines in the pattern of the unworked material, but most striking is the change in the relative intensities of certain lines. Whilst some lines (*e.g.*, the doublet 113 and 122, the overlap of 004 and 023, and the overlap of 330, 215, 006, and 400) remain strong, other lines, originally of comparable intensity, become very weak and diffuse (*e.g.*, 212, 221, and the 222 (114, 300) overlap). More detailed examination reveals other changes ; the broadening of certain lines, including some occurring at quite small diffraction angles, is relatively great (*e.g.*, 212, the 222 (114, 300) overlap and the (124) 312 (unresolved doublet)). Moreover, the angles at which the maximum intensities occur are also affected by cold-working to an extent varying markedly with crystallographic direction. In Fig. 60*b*, for example, the movement in relation to neighbouring lines of the 212 line, the 222 (114, 300) overlap, and the (124), 312 doublet, to higher-angle positions may be recognized visually. The microphotometer records in Fig. 62 illustrate, perhaps more clearly, examples of the changes to which reference has been made. These records were taken from " Crystallex " films, which were made under similar conditions of exposure and development.

The patterns described were obtained from specimens reduced about 90% by slow compression and

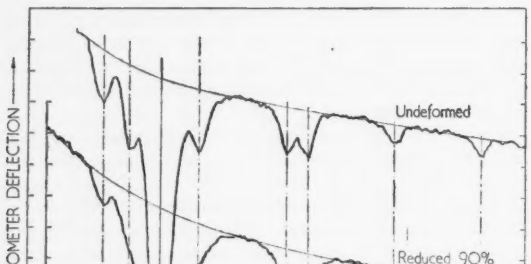


Fig. 62—Microphotometer records taken from " Crystallex " films

were examined on a surface perpendicular to the compression axis. The results were similar, irrespective of the degree to which surface material was polished away from the surfaces examined. Above 70% reduction, the observed changes were generally similar, but they became noticeably less with lower reductions.

At this stage, interpretation of observed changes was difficult. Since the carbide must be examined within the steel matrix, the diffuse lines given by the cold-worked carbide are masked by the incoherent scattering of the material as a whole and, with the apparatus available at present, it has not been possible to obtain useful photometer records of the majority of carbide lines given by the worked specimens.

The changes in the diffraction pattern which have been described bear resemblances to those given by layer structures with ' mistakes ' in their structural periodicity (*e.g.*, the effect of random variations in interlayer spacing in certain silicates on the one hand, and the effects of planar fragmentation, as in graphite, on the other). In the latter case the crystal fragments have a plate-like form, and Warren[33] has shown that those reflections which are faint and diffuse, owing to the two-dimensional character of the crystals, may be displaced towards higher-angle values by an amount dependent on the effective thickness of the layers. For this reason it was not at once concluded that the larger line shifts in the carbide pattern were necessarily associated with a contraction in the interlayer spacing.

In the present instance, however, we must consider not only the influence of residual elastic strains and possible fragmentation, but also the directionality of the change, including preferred-orientation effects. Experimental investigation of these factors has given evidence supporting the conclusion that the line shifts do represent a change in the interlayer spacings.

Sections were prepared parallel to the compression axis of cold-worked specimens (*i.e.*, perpendicular to the sections so far described) and also in several intermediate directions. These specimens had received 80% reduction in height and were polished but not etched, as before. The diffraction pattern obtained from a section parallel to the compression axis, with the X-ray beam perpendicular to the compression axis, is shown in Fig. 60*c*. There are several notable differences from the patterns obtained from sections perpendicular to the compression axis. The patterns given by intermediate sections had an intermediate character. The influence of varying the direction of the X-ray beam relative to the compression axis on a given section, to obtain further information of possible preferred orientation, was also examined. Finally, the positions of these lines were measured, using a travelling microscope, and the intensities were estimated visually. The results will be discussed with those of the experiment following.

A section perpendicular to the compression axis in a specimen having 90% reduction in height, tempered *in vacuo* at progressively increasing temperatures for periods of 15 min. at each temperature, was examined by X-ray after each tempering. Some of the results are illustrated in Fig. 61, in which the tempering temperatures are quoted against the corresponding patterns.

Very little change was observed after tempering up to 250° C. Above 250° C., recovery of cementite line sharpness was evident. Recovery of both line sharpness and position were marked in the temperature range 320–400° C. and appeared nearly complete at 480° C. Above this temperature, although the position and sharpness of the lines were similar to those given by cementite in the original unworked sample, there remained a modification in the relative intensity values. No change was noted in the cementite pattern as a result of annealing in the temperature range 600–750° C., and it was necessary to raise the temperature sufficiently to take most of the cementite into solution in the austenite (900–950° C. for this hyper-eutectoid steel) to restore the relative intensity values to those of the original sample.

Finally, this annealing experiment was repeated with a section parallel to the compression axis. Recovery of line sharpness and position was observed within the same temperature range, and after annealing at 600° C. there was a residual change in relative intensities which differed from that of the perpendicular section.

In Fig. 60 the patterns given by the ' as worked ' sections (*b* and *c*) and the sections which were heavily deformed and then annealed at 600° C. (*d* and *e*) are compared with the pattern given by an undeformed specimen (*a*). Sections (*b*) and (*d*) were perpendicular, and sections (*c*) and (*e*) were parallel, to the compression axis.

Discussion of the Changes in Cementite Indicated by the X-Ray Examination

No evidence has been found of any entirely new structure produced in cementite as a result of cold-working ; nevertheless the cementite particles in steel are greatly affected by the strains induced by severe cold-working of the steel.

The observed changes in the diffraction patterns are of two types, both of which have a directional charac-

ter. The first, involving line-broadening with a corresponding reduction in maximum intensity and also changes in line positions, shows recovery in the temperature range 200–500° C. After annealing at 600° C., recovery of both line sharpness and line position is virtually complete.

For reflected rays observed in a given plane, there remains unchanged after annealing at temperatures below the solution temperature of cementite in austenite, a modification in the relative intensities of the lines in the carbide pattern. Observations of the distribution of these intensity changes which remain after annealing at 600° C. are consistent with those which would arise from the development of preferred orientation of the carbide and, since measurement has shown that both line sharpness and line position are fully restored by annealing at 600° C., this explanation appears most likely. The observed changes suggest that a crystallographic direction in the neighbourhood of the [001] direction tends to be parallel to the compression axis. In regard to the orientations of individual reflecting planes relative to the specimen as a whole, the incident X-ray beam made an angle of 38° with the surface of the specimen ; therefore the majority of reflections with which we are concerned, *i.e.*, those lying between the ferrite lines 110 and 211, are given by planes which are within 12° of being parallel to the prepared surface of the specimen.

Considering the unannealed worked specimens, in which changes of the first type are superimposed on those ascribed to preferred orientation, the changes in position of the carbide lines are also dependent on the relation of the planes concerned to the direction of straining. Although the films do not permit a very accurate estimation of the strains, film measurement has shown that, in the direction of compression, there is a general contraction in the mean spacing of the planes ; whilst in directions perpendicular to the direction of compression there is a general increase in the mean spacing of the planes of the carbide structure. In a given direction in the specimen, the measured changes in the spacing of the ferrite structure are, in each case, of opposite sign to those in the cementite and are of a smaller magnitude. This agrees with the observations, on the behaviour of the ferrite, made in Section III, using more accurate back-reflection technique, and it supports the conclusions concerning the nature of the textural stress system between ferrite and cementite which develops as a result of the plastic deformation of steel. In the case of the cementite, however, both the movement and the broadening of the lines vary greatly with crystallographic direction. For example, the 212 line and 222 (114, 300) overlap are affected to a relatively great extent.

If the ferrite is etched away from the carbide particles on the surface examined (Fig. 59*b*) both the additional broadening and the movement of the lines of the cementite pattern are eliminated. There remain only those changes which have been ascribed to preferred orientation. There is, therefore, a very close similarity between Fig. 59*b* and Fig. 60*d*, the latter corresponding to a condition in which the strains have been removed by annealing. This supports the conclusion that the strains in the cementite particles are of an elastic nature and that they are maintained by the constraining effect of the surrounding ferrite.

On the other hand, to explain the dilatation results in Section I, it has been assumed that, at elevated temperatures, release of the textural strains between cementite and ferrite is accompanied by plastic strain of the cementite particles. The annealing experiments described in this Section show that most of the recovery of both line breadth and ring diameter in the cementite pattern occurs in the temperature range 200–500° C. As expected, this is coincident with the temperature range in which the same features of the ferrite pattern also recover. These results are also in agreement with those of Section III and later work. Whatever the mechanism of recovery of the cementite, it evidently has little influence on the existing preferred orientation of the particles.

One interesting fact brought to light by this investigation is that quite large changes in certain inter-atomic distances in the cementite may be brought about by severely cold-working the steel. For example, in the case of 212 planes parallel to or perpendicular to the compression axis, the mean change in spacing appears to be of the order of $\frac{3}{4}\%$ (contraction in the direction of compression, expansion perpendicular to this direction). Since these lines are also greatly broadened, the maximum variation of this spacing in a cold-worked sample almost certainly exceeds 2%. Moreover, since these observations have been made at free surfaces of the specimens, they will to some extent underestimate the strains imposed on cementite particles in the interiors.

At this stage these considerations are of interest in seeking an explanation of the influence of cold-work on the cementite Curie point change. At present, it seems likely, in view of the results of this X-ray investigation, that the modified rate of change of magnetic saturation with temperature is associated with a deranged structure rather than with a new structure in the cementite. Conceivably the changes in inter-atomic distances, by modifying the exchange interaction factor which influences the alignment of electron spins in a ferromagnetic substance, may, in effect, cause a ' smoothing out ' of the Curie change over a larger temperature range.

It is hoped to extend this X-ray investigation, using a monochromator in conjunction with a 19-cm. camera, which should permit a more accurate estimation of lattice strains. In addition to the plain carbon steel, a high-carbon high-chromium steel containing the trigonal carbide is now being examined. Up to the present, results suggest that the changes in this carbide are less marked than those in cementite.

Section VI—EFFECT OF COLD-WORK ON HYDROGEN IN STEEL

With U. V. Bhat, B.Sc., Ph.D., and H. K. Lloyd, B.Sc., Ph.D.

SYNOPSIS

The effect of cold-work upon hydrogen in steel at room temperature has been studied by means of an electrolytic method. It is shown that cold-work decreases the rate of hydrogen diffusion and increases the saturation. The correlation of these two properties with changes in hardness and density is discussed. In heat-treated specimens there are indications that the state of division and distribution of the cementite present plays a part in determining the rate of hydrogen diffusion in steel.

THIS Section is primarily concerned with the effect of cold-work on hydrogen diffusion and saturation in steel. The experiments were carried out at room temperature, and hydrogen was generated at the surface of the steel specimen by an electrolytic method. For hydrogen diffusion, the amount of gas diffusing through a hollow cylindrical specimen of uniform wall thickness was measured. The specimen was partly immersed in an electrolytic bath, and the depth of immersion was constant throughout the experiment. The hydrogen which diffused through the cylindrical wall was collected inside the specimen and displaced paraffin oil in a graduated tube. For saturation experiments, solid specimens were completely immersed in an electrolytic bath during the treatment. The hydrogen content, which represents the amount of hydrogen absorbed by the specimen during the electrolytic treatment, was subsequently determined by hot extraction in vacuum. The arrangement of these experiments has been given in detail in a previous paper.[9]

In electrolytic experiments, the surface conditions of the specimens are extremely important. To obtain reproducible results, a clean surface, free from machining marks, cracks and other defects, sludge, and oxides, should be maintained throughout the experiment. With these precautions, agreement to within 10% was obtained for both diffusion and saturation with similar specimens under identical conditions.

In all cases, where cold-drawn specimens are concerned, bars of different diameter were drawn to a given size to give various degrees of cold-work. This ensured a similar surface condition for all specimens and avoided any uncertainty if the cold-working was followed by machining. With undrawn or heat-treated specimens, the machined surface was carefully polished and cleaned. No attempt was made to activate the surface of either cold-drawn or undrawn specimens by etching.

For the work on hydrogen diffusion, three different sizes of specimen were employed (*A*, *B*, and *C* in Fig. 63), in accordance with the following details :

	Type *A*	Type *B*	Type *C*
Dimensions of specimen :			
Dia., in.	0·250	0·213	0·330
Length, in.	3	3	2½
Dimensions of axial hole drilled from one end			
Dia., in.	9/64	1/8	7/32
Depth, in.	1 17/32	1 17/32	2¼
Corresponding wall thickness of hollow tube, in.	0·055	0·044	0·055
Depth of immersion in electrolytic bath, measured from closed end, in.*	2¼	2¼	1½
Current density, amp./sq. cm.	0·304	0·309	0·300

Specimens of type *B* were used in the grain-size experiments, in which steel *A*2, treated to different grain sizes, was tested. Specimens of type *C* were used in the diffusion experiments in which cold-drawn specimens of steel *A*2 were tested after tempering to different temperatures. For all the remaining diffusion experiments, specimens of type *A* were used.

Hydrogen saturation experiments were carried out on *A*2 and *D*2. For *A*2, the specimens were relatively large, ½ in. dia. by 4 in. long, and weighed about 100 g. The time of treatment in the electrolytic bath was 96 hr., using a current density of 0·0825 amp./sq. cm. With *D*2, large bars could not be reduced by cold-drawing to the same extent as *A*2, and the specimens for hydrogen saturation were 0·277 in. dia. by 4 in. long, weighing approximately 30 g. With these smaller specimens, 24 hr. was adopted for the electrolytic treatment of *D*2, using a current density of 0·215

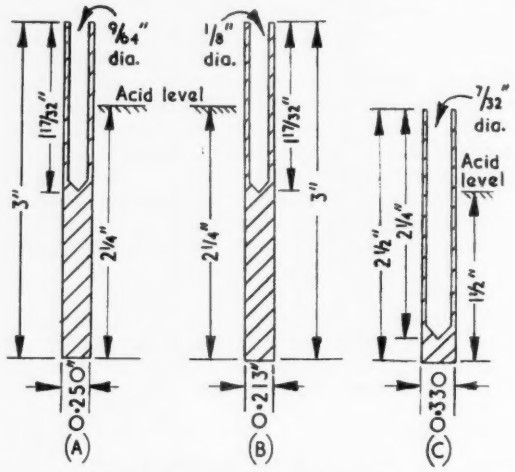


Fig. 63—Details of specimens used for hydrogen diffusion at room temperature

amp./sq. cm. To increase the accuracy of hydrogen determination of the small specimens, a special vacuum tube proportional in size to that of the saturation specimens was constructed for hot-extraction.

The results of the diffusion and saturation experiments are described under separate headings. In the course of the investigations, certain results on the effect of composition, structure, and grain size of the steel upon hydrogen diffusion were obtained and these are included in this Section.

EFECT OF COLD-WORK ON HYDROGEN DIFFUSION

As-Drawn Specimens

Steels *A2*, *C2*, *D2*, and *N23* were investigated in the as-drawn condition. The diffusion specimens were type *A*, as shown in Fig. 63. The evolution curves obtained for hydrogen diffusion are given in Fig. 64. The time taken for the evolution to commence was different for each steel, and for a given steel it increased with increasing reductions by cold-drawing. During the experiment, a certain time elapsed before 'steady' conditions were reached; under these conditions, the rate of evolution was constant, as will be seen from the evolution curves in Fig. 64. This constant rate was maintained as long as the surface of the specimen remained bright and intact, *viz.*, for several hours to a day or more, depending on the specimen. After a considerable period of constant rate of evolution, the surface of the specimen began to tarnish and the rate of evolution invariably fell off. At this stage, even a thorough cleaning of the specimen surface did not completely restore the original rate of evolution and the experiment was stopped.

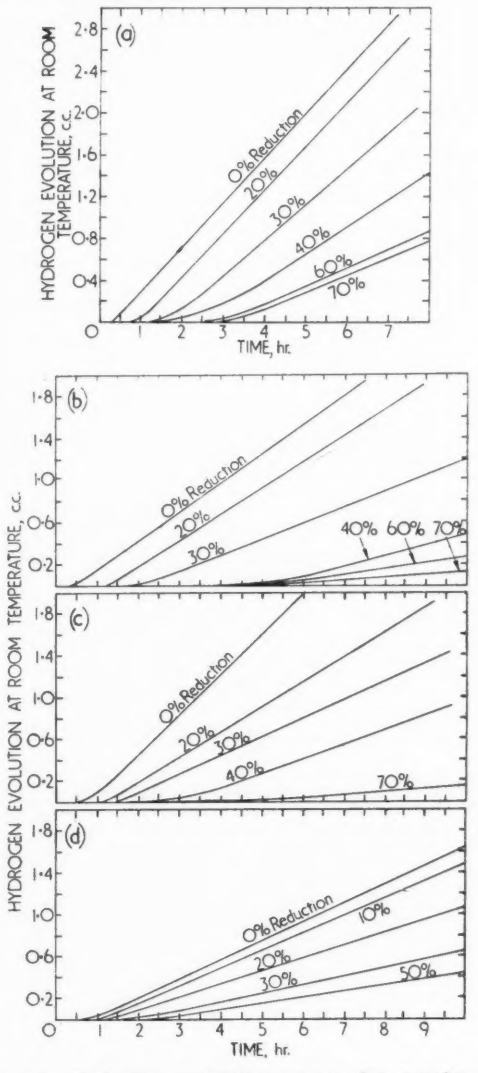


Fig. 64—Hydrogen evolution curves for specimens of (*a*) steel *A2*, (*b*) steel *C2*, (*c*) steel *D2*, (*d*) steel *N23*, cold-drawn to various reductions

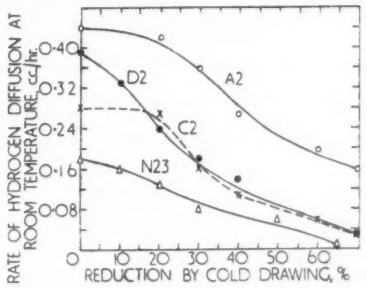


Fig. 65—Effect of cold-work on the rate of hydrogen diffusion at room temperature for steels *A2*, *C2*, *D2*, and *N23*

The constant rate of evolution which is given by the slope of the straight-line part of the curves in Fig. 64 is taken as a measure of the rate of hydrogen diffusion. Expressed in cubic centimetres per hour, the rates of diffusion for the different specimens are plotted against the degree of cold-drawing, in Fig. 65, as four curves representing the four steels. These data, together with the hardness values and other information concerning the diffusion specimens are summarized in Table II.

Table II and Fig. 65 show that the rate of hydrogen diffusion decreases with the degree of cold-drawing for the four steels tested, and the general trend of the four curves is very much the same. If an analogy can be drawn between hydrogen diffusion and thermal conduction, it should follow that, other things being equal, the rate of hydrogen diffusion would be expected to be lower in a hardened than in a soft specimen. Although this argument fits in with the present results, difficulties arise if they are treated quantitatively.

In the case of the low-carbon steel *A2*, for example, the observed rate of evolution changes from 0·44 c.c./hr. for the undrawn specimen to 0·16 c.c./hr. for the 70% reduction specimen, a decrease of over 60%. Such a large decrease would appear to be incompatible with theoretical considerations. In theory, the diffusivity, D, is given as :

$$D = Ae^{-\frac{Q}{RT}}$$

where R is the gas constant, T the absolute tempera-

Table II

HYDROGEN DIFFUSION RESULTS ON COLD-DRAWN SPECIMENS

Reduction by Cold-Drawing, %	Hardness, V.P.N.	Time from Switch-on to Start of Hydrogen Evolution, min.	Rate of Evolution, c.c./hr.	Condition of Specimen After Experiment
		Steel *A2* (Normalized before Cold-Drawing)		
0	98	18	0·44	Intact
20	187	45	0·42	,,
30	199	72	0·36	,,
40	206	75	0·27	,,
60	221	150	0·20	,,
70	223	165	0·16	,,
		Steel *C2* (Normalized before Cold-Drawing)		
0	156	25	0·28	Few blisters, otherwise intact
20	232	80	0·27	Intact
30	242	110	0·16	,,
40	249	240	0·11	,,
60	268	270	0·06	,,
70	276	303	0·03	,,
		Steel *D2* (Lead-Patented at 480° C. before Cold-Drawing)		
0	290	35	0·39	Intact
20	317	70	0·24	,,
30	319	85	0·18	,,
40	320	108	0·14	,,
70	354	135	0·03	Very slightly attacked
		Steel *N23* (Fully Softened at 650° C. before Cold-Drawing)		
0	301	42	0·18	Intact
10	314	65	0·16	,,
20	323	75	0·13	,,
30	329	96	0·08	,,
50	342	140	0·06	,,
65	353	480	0·01	Slightly attacked

Note—These results are based on the average values of a duplicate set of experiments, the agreement between the two sets being within 8% in all cases

ture, Q the activation energy of diffusion, and A is related to the 'jumping frequency' for a given atom a and the distance between atomic planes in the direction of diffusion d; thus $A \sim ad^2$. Provided that the mechanism for diffusion and the type of atoms concerned remains the same, Q can be treated as a constant; A, being proportional to the square of the distance between atomic planes, might not remain constant, but the effect of cold-work upon the lattice spacings is small. On these considerations, the very large decrease in the observed rate of hydrogen diffusion would hardly be expected.

Diffusion processes are primarily dependent on the concentration gradient. With electrolytic experiments, the surface conditions of the specimens are important and there is always the possiblity that the concentration of the hydrogen atoms at the surface may not be the same for the different specimens, in spite of a given current density. Another uncertainty is connected with the relatively short duration for which some of these experients could be maintained, for reasons already given. This would mean that some of the specimens may not be completely saturated and a steady concentration gradient would not be reached. These variables are difficult to control and, if existing, would be expected to affect the results. However, in view of the systematic variations of hydrogen diffusion with increasing degrees of cold-working, and the opposite trend between diffusion and saturation in the case of *A*2, as will be shown later, it is thought that the observed decrease in the rate of hydrogen diffusion in cold-worked iron specimens is partly due to the occlusion of molecular layers of hydrogen at mosaic boundaries or disjunctions, as suggested in a previous paper.[34]

With regard to hydrogen diffusion in steel, two further points should be borne in mind, *viz.*, the breakdown of the cementite lamellae into particles, and the fibre structure produced by cold-working. On the assumption that cementite is less permeable to hydrogen than is ferrite, the breakdown of cementite lamellae into particles should result in an increased rate of hydrogen diffusion. This effect, however, will largely depend on the initial structure of the specimen. The fibre structure may be regarded as being made of alternate layers of cementite and ferrite, and is usually associated with pearlitic or lamellar structure after heavy drawing. In such a case, it is extremely probable that the rate of hydrogen diffusion in the specimen may differ with different directions. In the present experiments the rate of diffusion was measured mainly in the transverse direction of the wire, and the values obtained were presumably the lowest. The other extreme, which

gives the fastest rate of hydrogen diffusion, might be along the longitudinal direction of the specimen.

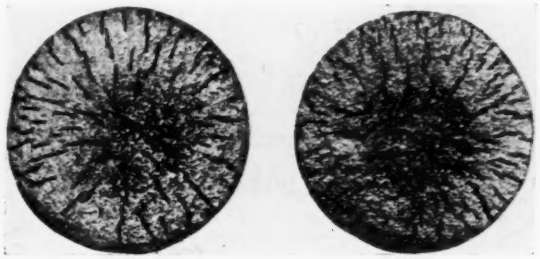
Returning to the results given in Table II, the time taken for the evolution to begin is in general agreement with the rate of diffusion observed. Thus, the period was longer if the rate of diffusion was lower. Another factor which governs this period would be the saturation value, or the ' apparent ' solubility, of the specimen. As will be shown later, apparent hydrogen solubility in steel at room temperature increased very rapidly with the degree of cold-working.

Sectioning and examination of the diffusion specimens, after removal from the electrolytic bath, showed that the solid portion of the 50% and 65% reduction specimens of *N*23 contained many internal cracks. As shown in Fig. 66, both specimens contained both radial and random-type cracks. Since the cold-drawn specimens were free from cracks before the diffusion experiments, such cracks must have been formed during the electrolytic treatment when hydrogen was introduced into the specimens. In the authors' experience, these were the only instances in which numerous internal cracks were produced in steel by introducing hydrogen at room temperature, a rather important feature which may help to dispel the view so often expressed that the formation of hair-line cracks in steel must necessarily be associated with thermal transformations. No cracks were observed in any of the other specimens in Table II after the diffusion experiments.

Cold-Drawn and Tempered Specimens

Cold-drawn specimens (70% reduction) of *A*2 were tempered *in vacuo* at various temperatures for 1 hr., after which hydrogen diffusion at room temperature was measured, as with the previous experiments. The diffusion specimens were of the type *C* shown in Fig. 63. The results obtained, together with the hardness values, are given in Fig. 67.

In Fig. 67, the curve relating hydrogen diffusion with tempering temperature is almost the opposite of that showing the variation of the hardness on tempering. Thus, up to 500° C. the decrease in hardness was relatively small and the increase in hydrogen diffusion was correspondingly slight. Between 500° and 600° C., however, recrystallization took place, which gave rise to a marked softening of the specimen and a sharp increase in the rate of hydrogen diffusion.



(*a*) 50% reduction in area
(*b*) 65% reduction in area

Fig. 66—Transverse sections of cold-drawn specimens of steel *N*23 after electrolytic diffusion at room temperature

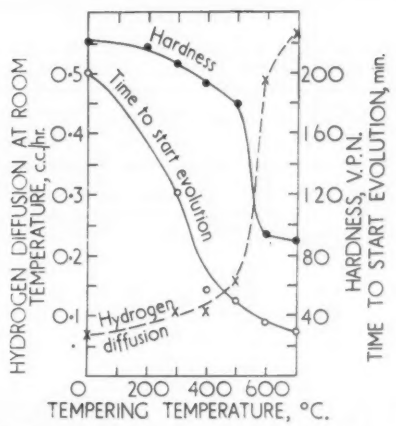


Fig. 67—Variation of hydrogen diffusion at room temperature for cold-drawn specimens of steel *A*2 (70% reduction), tempered for 1 hr. at various temperatures

During the diffusion experiments, the time taken for the hydrogen evolution to begin, as observed inside the specimen, was different for specimens tempered at different temperatures. As shown in Fig. 67, this period decreases with increasing tempering temperature. This is to be expected from the hydrogen diffusion and saturation results. Whilst the rate of hydrogen diffusion in this case increases with a decrease in the hardness of the specimen on tempering, the hydrogen saturation was just the opposite, as will be described under the next heading.

EFFECT OF COLD-WORK ON HYDROGEN SATURATION

As-Drawn Specimens

Results for steels *A*2 and *D*2 are summarized in Table III.

The results for *A*2 have been reported in a previous paper[34] in graph form, and are reproduced in Fig. 68*a*, to be compared with the results for *D*2 in Fig. 68*b*. Table III and Fig. 68 show that the amount of hydrogen which could be introduced into the two steels under the respective experimental conditions increased on cold-working. Using a current density of 0·0825 amp./sq. cm., the saturation value at room temperature for *A*2 in the soft condition was only about 2 c.c./100 g., but was increased to 22·2 c.c./100 g. when the steel was cold-drawn 70% reduction. Similarly, the saturation value for *D*2, using a current density of 0·215 amp./sq. cm., was increased from 6·2 to 29·3 c.c./100 g. for the same amount of cold-drawing. Before cold-drawing, *D*2 was lead-patented. With a different initial treatment, the saturation value for the undrawn specimen might have been different.

The hydrogen saturation curve for *D*2 bears a close relation to the work-hardening curve (Fig. 68*b*), but the correlation is not so good with *A*2 (Fig. 68*a*). Without dwelling upon any possible effect of the presence of carbon on hydrogen saturation in steel, it seems that the difference between the two steels in

Table III

HYDROGEN SATURATION RESULTS FOR COLD-DRAWN SPECIMENS AT ROOM TEMPERATURE

Specimen	Reduction by Cold-Drawing, %	Hardness, V.P.N.	Hydrogen Content, c.c./100 g.	Condition of Specimen after Saturation
Steel *A2* (0·06% C). Dimensions of specimens, ½ in. dia. × 4 in. long. Period of saturation, 96 hr. Current density, 0·0825 amp./sq. cm.				
A	0	98	1·93	Intact
B	10	158	2·40	,,
C	20	187	5·60	,,
D	30	199	6·45	,,
E	50	209	12·7	,,
F	70	223	22·2	,,
Steel *D2* (0·59% C). Dimensions of specimens, 0·277 in. dia. × 4 in. long. Period of saturation, 24 hr. Current density, 0·215 amp./sq. cm.				
A	0	290	6·2	Intact
B	10	305	12·5	,,
C	20	317	15·0	,,
D	30	319	14·8	,,
E	50	324	17·0	,,
F	70	354	29·3	Slightly attacked

this particular respect may be largely due to the different stress distribution across the section of the cold-drawn specimens. As shown by the X-ray results in a previous Section, the 70% reduction specimen of *A2* showed a relatively large stress gradient across the wire section, whereas such variations in a similar specimen of *D2* were small. With lower reductions, the difference in stress distribution across the section of the cold-drawn specimens would be expected to be greater. It seems to be clear that the stress gradient across the section of a cold-drawn specimen will be mainly governed by two factors, *viz.*, the size of the specimen, and the initial hardness of the material. The larger the section and the softer the material, the greater will be the difference in stress distribution across the specimen after cold-drawing. Bearing these factors in mind, the different trend in hydrogen saturation between *A2* and *D2*, with respect to their work-hardening curves, might be understandable.

It has been stated in a previous paper[34] that the hydrogen introduced into the steel at room temperature by electrolytic treatment is mainly in occluded form. The increase in occlusion has been assumed to be due to the production of additional internal cavities or voids which may possibly be identified with mosaic boundaries or disjunctions. In this way, it was possible to correlate the hydrogen saturation results on *A2* with the decrease in density brought about by cold-working.

Although *A2* was supplied as an ingot iron, it was, in fact, a low-carbon steel, as can be judged from its manganese and silicon contents in Table I (*see* p. 371). Unlike *A3* and *A1*, *A2* was fairly clean and free from oxide inclusions. The decrease in density brought about by cold-drawing (70% reduction) was of the order of 0·1%, a figure used previously[34] to account for the amount of hydrogen occluded in the cold-drawn specimen after the saturation experiments. Although similar calculations have not been made for other specimens cold-drawn less than 70% reduction, it is interesting that, up to 70% reduction, the increase in hydrogen saturation as shown in Fig. 68*a* for *A2* bears a close relation to the decrease in density in Fig. 12, curve 1 (Section I) for *A1*, with respect to the degree of cold-drawing up to 70% reduction.

With *D2*, it does not seem that the increase in hydrogen saturation brought about by cold-working can be correlated directly with the decrease in density, as with *A2*. If the density data on *D1* (Fig. 12, curve 2 (Section I)) are taken as being applicable to *D2* because of their similar carbon contents, then the decrease in density at 70% reduction would be about 0·27% for *D2*, as compared with about 0·12% for *A2*. The hydrogen saturation values for 70% reduction specimens were 29·3 c.c./100 g. for *D2* and 22·2 c.c./100 g. for *A2*. Even if the difference in current densities is ignored (the current density for *D2* was much higher than that for *A2*), it is clear that the hydrogen saturation values are not in proportion to the relative amount of decrease in density for the two cases.

If the difference in the decrease of density between *A2* and *D2* after drawing 70% reduction is disregarded, their hydrogen saturation values may be compared on a common basis with respect to the current density. The relation between current density and the equivalent external hydrogen pressure is given empirically by Borelius and Lindblom[35] as

$$p = 17{,}000\ I \text{ atm.}$$

where I is the current density in amp./sq. cm. and p is the equivalent external hydrogen pressure. Using this relation and assuming that hydrogen saturation in steel at room temperature also obeys the square-root law, the saturation value for *D2*

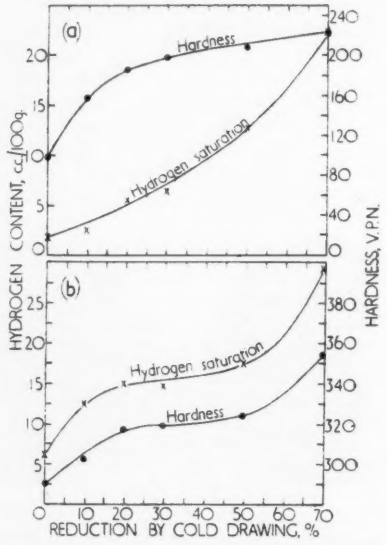


Fig. 68—Variation of hydrogen saturation with degree of cold-work for specimens of (*a*) steel *A2*, (*b*) steel *D2*

corresponding to a current density of 0·0825 amp./sq. cm. should be 3·84 c.c./100 g. for the undrawn and 18·2 c.c./100 g. for the 70% reduction specimen. If, however, the hydrogen absorbed in the steel was mainly in the occluded form, as it is assumed to be, the saturation value should then be directly proportional to the external hydrogen pressure prevaling over the specimen. On such a basis, the hydrogen saturation for *D*2 corresponding to a current density of 0·0825 amp./sq. cm. would be 2·37 c.c./100 g. for the undrawn and 10·8 c.c./100 g. for the 70% reduction specimen. Whichever was the case, the increase in hydrogen saturation on cold-working was less for *D*2 than for *A*2.

Cold-Drawn and Tempered Specimens

The shape and size of the specimens and the conditions for electrolytic treatment were similar to those already described for as-drawn specimens. Tempering was carried out *in vacuo* and the time at the various temperatures was 1 hr. The results obtained on a series of specimens, cold-drawn 70% reduction and subsequently tempered at different temperatures, are given in Fig. 69 for *A*2 and *D*2, together with the corresponding hardness curves.

In Fig. 69*a*, although only five points are available for hydrogen saturation, the general trend, with the low-carbon steel *A*2, closely follows the hardness curve, and, in both cases, a rapid drop occurs at the recrystallization temperature (500–600° C.). Even after tempering at 600° C., the hydrogen saturation for the cold-drawn specimen (70% reduction) was still very high, at 10·6 c.c./100 g. ; the hardness value, however, was comparable to that of the undrawn specimen (Table III). It will be remembered that the saturation value for the undrawn specimen of this steel was only 1·93 c.c./100 g., which is far less than that indicated for the cold-drawn specimen tempered at 600° C. The difference in hydrogen saturation

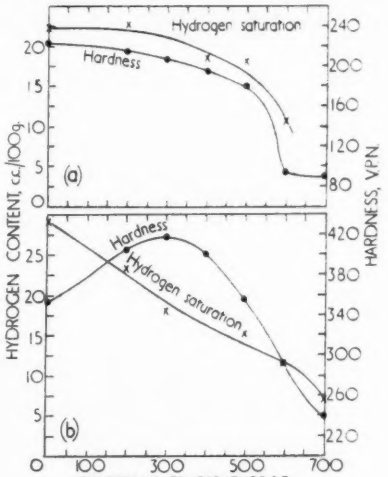


Fig. 69—Variation of hydrogen saturation for cold-drawn specimens (70% reduction), tempered for 1 hr. at various temperatures : (*a*) Steel *A*2, (*b*) steel *D*2

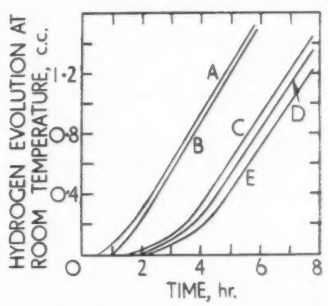


Fig. 70—Hydrogen evolution curves for specimens of steel *A*2 treated to give different grain sizes

in the two cases may be due to the difference in grain size. The grain size of the cold-drawn and tempered specimen would be much smaller than that of the unworked specimen, and a certain part of the grain boundaries may be effective for the storing and accommodation of hydrogen.

The results for the high-carbon steel *D*2, Fig. 69*b*, show that the hydrogen saturation of the cold-drawn specimens (70% reduction) decreases with increase of tempering temperature. Up to 300° C. the hardness of the cold-drawn specimens showed a continuous increase, as might be expected from previous results. The correlation between hydrogen saturation and hardness observed with the cold-drawn low-carbon steel *A*2, on tempering, therefore, did not exist in this case, at least up to 300° C. Taking into account the results for *A*2, showing that hydrogen saturation as well as the hardness of the cold-drawn specimen was not affected after tempering at 200° C. and was only slightly decreased at 400° C., the early and continuous drop in hydrogen saturation, whilst the hardness of the specimen increased, as in Fig. 69*b* for *D*2, may be rather significant. This phenomenon will be discussed later with other results.

EFFECT OF GRAIN SIZE ON HYDROGEN DIFFUSION

A number of bars of *A*2 (0·06% C) were cold-drawn to various reductions and subcritically annealed to give different grain sizes. The annealed bars were subsequently machined into hollow, cylindrical specimens of type *B* (Fig. 63) for hydrogen diffusion. The evolution of hydrogen inside the hollow specimen was recorded, as with the previous experiments, and the curves obtained are given in Fig. 70. As before, the slope of the curve, when steady evolutions had been attained, was taken as a measure of the rate of hydrogen diffusion. The results, and details of the specimens, are summarized in Table IV.

The rate of diffusion is plotted against the variation of grain size of the specimen in Fig. 71, which includes a duplicate set of points. The two sets agree to within 7%. Although the general tendency of the curve seems to indicate that the rate of hydrogen diffusion is slightly lower in smaller-grained specimens, such differences are within the margin of experimental error. It is concluded, therefore, that the increase of grain boundaries in iron has little effect upon hydrogen diffusion. This confirms the earlier findings of

Table IV

RESULTS FOR HYDROGEN DIFFUSION AT ROOM TEMPERATURE. STEEL *A2*, TREATED TO DIFFERENT GRAIN SIZES

Specimen	Reduction by-Cold-Drawing, %	Subcritical Annealing	Grains/mm.	Time between Switch-on and Evolution, min.	Rate of Diffusion, c.c./hr.
		°C. Hr.			
A	25·4	650 1	29	36	0·32
B	41·5	650 1	63	65	0·32
C	60·8	650 1	102	90	0·30
D	81·4	650 1	157	102	0·29
E	88·6	600 ½	178	128	0·28

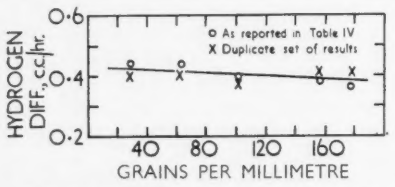


Fig. 71—Effect of grain size on the rate of hydrogen diffusion at room temperature for steel *A2*

Edwards,[36] as well as the results of Smithells and Ransley.[37]

On the other hand, Table IV shows that the time taken between switch-on and the beginning of hydrogen evolution, as observed inside the specimen, increases very markedly as the grain size of the specimen becomes smaller. This period is primarily dependent on two factors, *viz.*, the apparent hydrogen solubility and the rate of diffusion. Since the rate of hydrogen diffusion does not vary in the present case, the increase in this period with decreasing grain size could only mean that the ' apparent ' solubility of hydrogen in iron is greater in smaller-grained specimens. In other words, grain boundaries appear to play a part for the accommodation of hydrogen in steel. This is in line with the saturation results for *A2*, when comparisions are made between the undrawn specimen and the cold-worked and tempered (600° C.) specimen, as already described.

EFFECT OF STRUCTURE ON HYDROGEN DIFFUSION

Steel *D2* was treated to three different structures for the study of hydrogen diffusion, using specimens

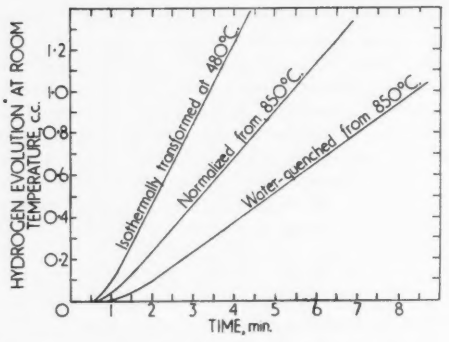


Fig. 72—Hydrogen evolution curves for steel *D2* treated to different structural conditions

of type *A*. The treatments and the results are given in Table V, and the evolution curves are plotted in Fig. 72.

Table V and Fig. 72 show that the rate of hydrogen diffusion differs with the thermal treatment given to the specimen. Although the specimen transformed at 480° C. was considerably harder than the normalized one, it showed a greater rate of hydrogen diffusion. This might be expected, assuming that cementite is less permeable to hydrogen than ferrite and that the presence of cementite as lamellar plates would be more obstructive to hydrogen diffusion than in particle form. The rate of hydrogen diffusion in martensite was the least, in accordance with the conception that hydrogen diffuses mainly through the lattice ; the presence of carbon atoms in the iron lattice and the highly distorted nature of martensite will both contribute to the retardation of the rate of hydrogen diffusion. In general, these results are in good agreement with those reported in a previous paper[9] for a 3¼% nickel steel, *S*69.

EFFECT OF COMPOSITION ON HYDROGEN DIFFUSION

Effect of Carbon

The results for *A*2, *C*2, and *D*2 already described are now collected and discussed to illustrate the effect of carbon on hydrogen diffusion in steel. To facilitate comparison, they are summarized in Table VI.

The results given in Table VI were obtained on specimens of type *A*. The rate of hydrogen diffusion at room temperature decreases with the increase of

Table V

RESULTS FOR HYDROGEN DIFFUSION AT ROOM TEMPERATURE. STEEL *D2*, TREATED TO DIFFERENT STRUCTURES

Specimen	Treatment	General Structure	Hardness, V.P.N.	Time between Switch-on and Evolution, min.	Rate of Diffusion, c.c./hr.
1	Normalized from 850° C.	Coarse lamellar pearlite and ferrite	202	39	0·22
2	Isothermally treated at 480° C.	Very fine cementite particles and ferrite	290	35	0·39
3	W.Q. from 850° C.	Martensite	850	45	0·14

Table VI

EFFECT OF CARBON CONTENT ON HYDROGEN DIFFUSION AT ROOM TEMPERATURE

Steel	Carbon, Content, %	Treatment	Hardness, V.P.N.	Time between Switch-on and Start of Evolution, min.	Rate of Diffusion, c.c./hr.
A2	0·06	N. 930° C.	98	18	0·44
C2	0·31	N. 900° C.	156	25	0·28
D2	0·59	N. 850° C.	202	39	0·22

Effect of Chromium

A nominal nickel steel, *N*22, and a nickel–chromium steel, *N*23, were used for the hydrogen diffusion experiments to illustrate the effect of chromium. Both steels were quenched from 850° C. and subsequently tempered at 650° C. to give a fully softened sorbitic structure before machining into diffusion specimens, for which type *A* was used. The results are given in Table VII.

A comparison between the results of *N*22 and *N*23 indicates that the presence of chromium decreases the carbon content of the steel. In making such comparison, the carbon in the different steels must be treated to a similar state of division and distribution. In the present cases, steel *A*2 contained insufficient carbon to form pearlite, but both *C*2 and *D*2 were treated to the same condition, *viz.*, ferrite and lamellar pearlite. The increasing time for the hydrogen evolution to begin, with the higher carbon content, is more or less in accordance with the decreasing rate of diffusion.

Table VII

EFFECT OF CHROMIUM IN HYDROGEN DIFFUSION AT ROOM TEMPERATURE

Steel	Brief Composition	Treatment	Hardness, V.P.N.	Time between Switch-on and Start of Evolution, min.	Rate of Diffusion, c.c./hr.
*N*22	0·36% C 3·28% Ni	W.Q. 850° C. and T. 650° C.	245	42	0·42
*N*23	0·32% C 3·29% Ni 0·87% Cr	W.Q. 850° C. and T. 650° C.	302	50	0·18

The rate of hydrogen diffusion in steel. The amount of chromium present in *N*23 was insufficient to give chromium carbides, and the distribution of the cementite in the two steels after heat-treatment was similar. The decreased rate of hydrogen diffusion was therefore mainly associated with the effect of chromium in ferrite.

In view of some of the uncertainties associated with electrolytic experiments already discussed, the present results on hydrogen diffusion should be taken only as qualitative indications.

Section VII—GENERAL DISCUSSION

SYNOPSIS

The results reported in the foregoing Sections are correlated and discussed. It is concluded that the austenite theory advanced in an earlier paper is valid only in special cases involving a sudden generation of intense heat during deformation. In normal processes of cold-working, the austenite theory is untenable and the change of properties is explained by the various effects of internal strains in ferrite and in cementite. In the past, whilst the effect of internal strains in ferrite is to some extent well known, the effect of such strains in cementite and of those arising from the mutual restraint between ferrite and cementite, upon the bulk properties of steel, has not been sufficiently realized. The increased hydrogen saturation in cold-worked steels has also been correlated with X-ray line-broadening, thus supporting the view suggested in a previous paper that the hydrogen introduced into steel at room temperature is mainly accommodated in occluded form at crystallite boundaries or mosaic disjunctions.

The present work was initiated to examine the validity of the austenite theory advanced in an earlier paper.[8] As the experiments progressed, it became clear that the austenite theory is valid only for special cases, involving sudden generation of intense heat during deformation. For example, austenite may be present in a localized band produced by subjecting a steel specimen to a severe blow under a falling weight (Section IV) or at the surface of a shear fracture resulting from failure by compression (Section V). In the former case, the deformation is extremely localized and the energy is imparted to the specimen at such a rapid rate that very high temperatures may have been reached at the localized part under virtually adiabatic conditions. In the latter case, heat generated by friction between the two fractured surfaces is believed to be responsible for the observed austenite formation. These conditions are quite remote from those encountered in normal cold-working processes. Indeed, the bulk of the results shown in this paper do not indicate the presence of either austenite or martensite in cold-drawn steels or in compressed test pieces.

When it was realized that the austenite theory is

untenable for general forms of cold-working, attempts were made to extend the work so that the work-hardening properties of steel may be correlated and explained on a rational basis. This led to a detailed study of some of the physical properties of steel before and after cold-working. A similar study was made some 40 years ago by Goerens,[38] but with the modern facilities and techniques now available the present work has the advantage of exploring certain new fields, and the results are considered to be more accurate than those shown by the early pioneer.

The effect of cold-work upon iron, as upon other pure metals, can be looked upon from two aspects, *viz.*, the setting-up of internal strains on both macroscopic and microscopic scales. Micro-strains are mainly associated with the distortion or warping of atomic planes. They are believed to be responsible for the well-known X-ray line-broadening and decrease of line intensity when X-ray patterns of cold-worked specimens are compared with those of annealed specimens. Macro-strains are characterized by a change in lattice spacing, and this change is different for different crystallographic planes and directions. Micro-strains affect mainly the structure-sensitive properties, notably the hardness and other mechanical properties. To a much less extent, they increase the electrical resistivity and decrease the density. Macro-strains, on the other hand, give rise to directional changes, as would be expected from their effect upon lattice spacing. In such a case, certain properties irrespective of structure-sensitiveness or insensitiveness may be affected to various extents and this effect may be superimposed upon those caused by micro-strains and crystal orientations. In view of these effects, it is clear that the interpretation of changes in properties in cold-worked metals is usually complicated.

With cold-worked steels, the picture is even more complex. Here we are dealing with a composite structure ; not only the effect of micro- and macro-strains in both the ferrite and the cementite has to be recognized, but the bulk properties must also be influenced by the state of division and distribution of these two constituents. There is reason to believe that micro-strains in a cold-worked steel are of a higher level than those in a similarly cold-worked iron. With regard to macro-strains, the mutual restraint between cementite and ferrite gives rise to textural stress which, although on a microscopic scale, may affect the lattice spacings of both cementite and ferrite in a cold-worked steel. The effect of macro-strains from such a source upon the bulk properties of steel would, in certain cases, be expected to be different from those associated with body or Heyn stresses.

The well-known fact that mechanical properties are particularly sensitive to the presence of micro-strains is also borne out by a correlation between the hardness and the X-ray line-broadening in the present experiments. Thus, both the hardness and the X-ray line width of ferrite increase in a similar manner with increasing degrees of cold-working, and this is true for low-carbon iron as well as for high-carbon steels (*cf.* Fig. 47 (III)* with Fig. 1*a* (I)). On the other hand, macro-strains may also affect the hardness, although to a much less extent. For example, O'Neill[39] has shown that the Brinell number of a steel specimen may be lowered by 10% when tested under elastic tension and by 5% when tested under elastic compression. Since the magnitude of the residual macro-strains is higher in a cold-worked high-carbon steel than in a cold-worked low-carbon iron and the distribution is also different in the two cases, the removal of such strains on heating may give rise to different effects upon the change of some of the properties observed.

Consider, first, the change of hardness on tempering. It has been shown that the hardness of a cold-worked high-carbon steel invariably increases on tempering and generally reaches a maximum at about 300° C. With a cold-worked low-carbon iron, the change of hardness after tempering in the same temperature range is very small. This difference is very difficult to explain unless the effect of elastic strains upon hardness is taken into account. In O'Neill's experiments, the ferrite grains in the longitudinal direction of the specimen would be under either uniform tension or compression, depending on the nature of the applied load. Such a condition is similar to the state of residual elastic strains in a cold-drawn high-carbon steel in which the (211) spacings of ferrite are shown to be under compression in the longitudinal and under tension in the transverse direction (Section III). Other spacings of ferrite may be assumed to be similarly affected because the balance of the residual stress system is maintained by the opposite signs of lattice strains in cementite, as indicated in Section V. Since O'Neill indicates that the hardness value of a steel specimen is lowered when tested under elastic strains, it is reasonable to assume that the removal of such strains will increase the hardness. Applying this argument to cold-worked steels, the recovery of the residual elastic strains in ferrite, which has been shown to take place rapidly above 100° C., may therefore be the cause of secondary hardening. Whilst this proceeds as the temperature increases, up to a certain point the increase in hardness will be intercepted by another process which causes softening, *i.e.*, when the removal of micro-strains becomes effective. Consequently, there will be an optimum tempering temperature for which the hardness of the specimen is at a maximum. It is interesting to note that the maximum increase in hardness obtainable by tempering a cold-worked high-carbon steel at 300° C. is about 10–15%. This compares very well with the 5–10% decrease in hardness observed by O'Neill, especially as—in view of the higher yield stress in cold-worked steels—the residual elastic strains in the present specimens may be much greater than those obtainable in soft steels under external loading.

Hardness is a structure-sensitive property, but thermal expansion is not. However, it has been shown in Section I that, on heating a cold-drawn high-carbon steel wire, marked dilatation changes give rise to a permanent increase in length and a contraction in diameter. This takes place mainly between

* A Roman numeral in brackets after a Figure number indicates the Section of the paper in which that Figure will be found.

150° and 450° C., during which the density of the specimen is hardly affected. Here again, cold-worked low-carbon iron behaves differently because no permanent increase in length or contraction in diameter has been detected after heating up to 450° C.

The dilatation changes in cold-drawn high-carbon steels mentioned above are consistent with the recovery of elastic strains in ferrite. Indeed, it has been possible to correlate the dilatation results with the change of X-ray ring diameter obtained in the longitudinal and transverse directions of the wire. Consider, for example, a 0·6% C steel (*D*1 or *D*2), cold-drawn 60% reduction from a lamellar structure, and compare the recovery of the (211) spacings of ferrite with the residual expansion in the longitudinal direction on tempering, Fig. 45 (III) and Fig. 7*b* (I). Not only is the shape of the curves similar, but the amount of residual compressive strains in ferrite, as represented by the change of (211) spacings in the longitudinal direction, is of the same order as the residual expansion observed.

In cold-worked low-carbon iron, the change of lattice spacings in ferrite is mainly due to the presence of body stresses. The mean strain in any given direction must be zero and the dilatation effect will be self-compensating ; therefore, no change in the dimensions of such specimens is to be expected until recrystallization sets in. This takes place above 450° C. and gives rise to a small contraction due to the recovery of density.

It has been pointed out in Section III that, in a cold-worked high-carbon steel, the residual elastic strains in ferrite are mainly imposed by the presence of cementite, which behaves differently during plastic deformation. The magnitude of such strains may be expected to vary with the amount and the state of division and distribution of the cementite present. Indeed, later experiments have confirmed this view, showing that with a 0·6% C steel, the residual lattice strains in ferrite after cold-drawing are much less for a spheroidized than for a lamellar structure. The difference varied with the reductions of the specimens, but from 20% reduction upwards, the magnitude of such strains in a cold-drawn spheroidized structure was generally less than half that found in a similarly drawn lamellar structure. These results again fit in with the dilatation experiments. Thus, a comparison of Fig. 8 (I) with Fig. 4*e* (I) shows that the dilatation effect is appreciably less for cold-worked sorbite than for cold-worked pearlite.

After heating to successively higher temperatures and subsequently cooling, the cold-drawn specimens show, on cooling, perfectly linear dilatation curves in all cases. For a given steel, the slope of these cooling curves is almost exactly the same, irrespective of the degree of cold-drawing and the temperature of heating. Again, as stated in Section I, " If, after the first heating, the same specimen was reheated and the dilatation curve was recorded, the dilatation curve followed a normal linear course as if the specimen had not been cold-worked, until the first heating temperature was reached. Above this temperature the specimen would then resume its cold-worked behaviour." This recording of facts not only indicates that the release of residual macro-strains in cold-drawn steels is mainly temperature-dependent, but also suggests that the dilatation changes observed should not be misconstrued to imply that the *true* thermal coefficient of expansion of steel is affected to any marked extent by cold-working.

The fact that the release of residual macro-strains during heating gives rise to a *permanent* change in the shape of the specimen necessarily means that some plastic yielding must take place. At first, it might be thought that, on heating a cold-drawn wire, it is the ferrite which will yield because cementite is generally regarded as brittle and therefore incapable of sustaining plastic deformation. This view, whilst reasonable and perhaps logical under normal circumstances, does not, however, fit in with the dilatation and X-ray results discussed above. Bearing in mind that the residual lattice strains in the ferrite are compressive in the longitudinal direction and tensile in the transverse direction, if the release of such strains is due to plastic yielding in the ferrite itself, the result will be a contraction in the longitudinal direction and an expansion in the transverse direction of the specimen. This is exactly opposite to the dilatation effect actually observed. To explain the dilatation results, it is necessary to assume the contrary, *i.e.*, it is the cementite which must undergo a certain amount of plastic yielding sufficient to allow the ferrite to recover elastically. In this connection, it is hardly necessary to point out that a constitutional change in the cementite may achieve the same purpose of plastic yielding as long as such a change will allow for the mutual restraint between the cementite and its surrounding ferrite to be released.

The behaviour of cementite, both during cold-working and on subsequent heating, appears to be one of the main factors determining the dilatometric properties of steel. When cementite is substituted by a different carbide, different results may be expected. This is shown by the dilatation curves for *CR*5 (3% Cr, 0·2% C). In Figs. 11*a* and 11*b* (I) the difference in dilatation—mainly from the point of view of longitudinal expansion—between cold-drawn and undrawn specimens is small when the steel is initially treated to contain chromium carbide (Cr_7C_3), but the difference is marked when cementite is present. As shown in a previous paper,[9] when this steel is transformed isothermally at 700° C. to give chromium carbide, the general structure is pearlitic. On transforming at 350° C., the steel shows an intermediate structure consisting of fine cementite particles uniformly distributed throughout the mass. Unless the difference in carbide constitution is taken into account in the two cases, the general structure alone will probably suggest a greater dilatation effect in cold-drawn specimens with the former size and distribution of carbide than with the latter.

It has been deduced that, in cold-drawn steels, residual macro-strains must also be present in cementite and they must bear opposite signs to those present in ferrite. In fact, this deduction has been confirmed by the experiments described in Section V, using a 1·2% C steel severely deformed by compression. The results show that, in a severely worked

specimen, the cementite structure is unmistakably in a state of residual elastic strain and the planes which appear to be most affected are the (212) spacings. The strains are gradually removed on heating and the temperature range over which this takes place is in general agreement with that observed for the recovery of the ferrite lattice spacings in cold-drawn wires.

The presence of residual lattice strains in cementite may be considered in connection with the observed disappearance of the normal cementite Curie point in steel after cold-working. It has been shown in Section I that when a high-carbon steel is cold-drawn more than 50% reduction, the Curie point of cementite becomes weaker and weaker (Fig. 20*d* (I)). At 90% reduction or more, the thermomagnetic curve of *E*1 (0·7% C) is perfectly smooth, showing no signs of a discontinuity corresponding to the normal Curie point of cementite at 200–250° C. (Fig. 23 (I)). The magnetic saturation of the steel at room temperature, however, is apparently unaffected. The cementite Curie point in cold-worked steels can be recovered by heating; a partial recovery takes place after heating to 400° C. and, from the shape of the thermomagnetic curves in general (Fig. 20*d* (I)), it appears that a complete recovery may be achieved by annealing the specimens below the Ac_1 temperature.

On theoretical grounds, it is generally believed that ferromagnetism is caused by electron spins which are parallel, and the essential condition for this, from a mathematical point of view, is that the function of the interchange interaction should be positive. In practical language, ferromagnetism is primarily dependent upon three main factors: the nature of the atoms concerned, the lattice structure, and the distance of the inter-atomic spacings. Forrer,[40] in a critical survey of relevant data on ferromagnetic materials, concluded that, for ferromagnetism to occur, the effective distance between the atoms must be about 2·7–3·0 Å. for manganese and iron, and about 2·4–2·5 Å. for cobalt and nickel. Large separations give rise to paramagnetism which varies with the temperature, and smaller separations to paramagnetism which is approximately independent of temperature. Stoner[41] has accepted the validity of Forrer's conclusions in their general character, but pointed out that the exact distances given for ferromagnetism must be taken as provisional because of a number of arbitrary features which had to be introduced in the treatment of the experimental data. However, the general importance of inter-atomic distance upon ferromagnetism cannot be denied, and the effect of cold-working upon the cementite Curie point in steel, as shown in Section I, might very well be attributed to the effect of residual lattice strains in cementite.

As described in Section I, when a 0·7% C steel (*E*1) was cold-drawn more than 50% reduction, the intensity of the cementite lines was weakened and at 90% or higher reductions, such lines became virtually invisible. In such a case, it is not possible to say whether there was any appreciable change in the lattice spacings of cementite after cold-working. However, by using a higher carbon steel (1·2% C) and carrying out the deformation by compression instead of by drawing, it has been possible to obtain X-ray patterns of cementite, even after reducing the specimen to less than 10% of its original height. Thus the results in Section V show that, after severe deformation, lattice strains and preferred orientation are evident in the cementite structure. The shifting of the (212) spacings due to the presence of residual lattice strains may amount to as much as 0·75%. Other lines are similarly affected, but with the relatively small camera size (10 cm.) employed and the diffuseness of the lines, the changes are not so apparent. Bearing in mind the temperature at which the position and the sharpness of the cementite lines recover, it seems very probable that the removal of the residual strains will restore the normal cementite Curie point in cold-worked high-carbon steels.

Since inter-atomic distance is one of the determining factors for ferromagnetism, and the effect would be expected to be particularly sensitive in the Curie point region, the authors are inclined to think that parameter changes, such as the displacement of the (212) or other spacings in cementite described above, may be responsible for the observed absence of cementite Curie point in severely cold-worked steels. In cementite, iron and carbon coexist, and the inter-atomic distances concerned will be twofold: the spacings between iron and iron on the one hand, and those between iron and carbon on the other. The presence of both co-valent and metallic linkage has greatly complicated the collective electron system which ultimately determines ferromagnetism or paramagnetism. Whilst the change of atomic spacings appears to be the most straightforward explanation to account for the effect of cold-work on the observed change of the cementite Curie point in steel, there may be other factors, for example, the effect of particle sizes upon magnetic domains. The exact nature of the domain structure is, however, not very clear, and data concerning the size of the domains in ferromagnetic materials are seriously lacking.

The thermomagnetic curves showing absence of cementite Curie point in tempered martensite (Section I) confirm the work of Antia, Fletcher, and Cohen.[16] Cohen maintained that the precipitated phase from martensite, on tempering below 300° C., was a transition product different from the normal cementite. Later on, Kurdjumov[22] and others produced X-ray evidence to show that the precipitated phase in tempered martensite was a carbon-rich constituent with a lattice structure different from that of cementite, but for obvious reasons they were unable to say precisely what lattice structure this precipitated carbon-rich phase actually possessed. At the same time, Heidenreich[23] and others carried out electron diffraction examination on tempered martensite and they showed a hexagonal phase believed to be isomorphous with iron nitride. Jack[12] contended that the hexagonal phase in tempered martensite, as shown by Heidenreich, could be iron carbo-nitride, which was found to decompose into cementite when heated to 400° C. In fact, Wever and Naeser[43] analysed carbide residues isolated from steels tempered at different temperatures and, as early as 1934, it was shown that FeC was formed up to 250° C., Fe_2C up to 600° C., and the normal cementite (Fe_3C) at higher

temperatures. Wever and Naeser's experiments are not free from criticism, however, because the carbides are known to undergo a certain amount of decomposition during or after electrolytic separation. Unless proper precautions were taken to prevent decomposition or the graphite was removed from the residues before they were analysed, their results might be in error. Such an error could have led to the conclusion that the carbides present in steels treated at low temperatures apparently contained more carbon than the normal cementite. A general review of the published work shows that, whilst the transition product in tempered martensite may be different from the normal cementite and therefore explains the absence of cementite Curie point, the exact nature of this product is by no means settled.

Returning to the properties of cold-worked steels, another interesting feature shown in the present work is the change of electrical resistivity. In dealing with this property, structural changes concerning the state of division and distribution of cementite are important and it should be noted that the measurements are taken in the longitudinal direction of the cold-drawn wires. As shown in Section II, with ingot iron the effect of cold-drawing brings about an increase in resistivity at room temperature to the extent of 0·6% at 40% reduction and about 2% at 80% reduction (Fig. 38*c* (II)). In this case, the amount of cementite present is extremely small and therefore the effect associated with cementite distribution does not enter. The increase in resistivity, as in the case of cold-worked ingot iron, is to be attributed mainly to the presence of micro-strains produced in ferrite by cold-working. Micro-strains are associated with dislocations or the warping of atomic planes which disturb the regular atomic arrangement of the lattice structure. It is clear that, insofar as ferrite is concerned, the resistivity must increase even in steel. However, owing to the alignment of the cementite in the drawing direction, the increase in resistivity contributed by cold-worked ferrite is offset against a structural change which decreases the resistivity in the longitudinal direction. The bulk resistivity of a steel after cold-drawing, as measured along the wire axis, may therefore show either an increase or a decrease, depending mainly upon its carbon content and the degree of drawing. For a given steel and a given degree of cold-drawing, the resistivity will vary with the initial structure of the specimen.

With the 0·58% C steel *D*1, for example, the bulk resistivity, measured in the longitudinal direction after cold-drawing, shows a *decrease* instead of an increase, as with the ingot iron *A*1. The decrease varies with the degree of drawing as well as with the initial structure of the specimens (Figs. 38*a* and *b* and 39 (II)). With a pearlitic structure (lead-patented) in which the cementite is present as lamellae the decrease in resistivity at 70% reduction is about 5½% (Fig. 38*a*). When the same steel is drawn from a sorbitic structure in which the cementite is present as spheroidized particles, the corresponding change is only 1·4% (Fig. 39). These results can be explained on the basis of the change of cementite distribution brought about by the effect of cold-drawing, as follows :

The resistivity of cementite is known to be much higher than that of ferrite, therefore the alignment of cementite, as given by the fibre structure, will tend to lower the bulk resistivity in the longitudinal direction of the wire. Taking the resistivity of cementite ρ' as 45 microhms/cm., and that of ferrite ρ as 10 microhms/cm., and assuming certain structural arrangements between cementite and ferrite, it has been possible to treat the effect of cementite distribution upon the change in the bulk resistivity of steel on a mathematical basis. The structures assumed in the theoretical treatment are : (1) an ideal lamellar structure consisting of alternate layers of cementite and ferrite with every layer lying across the whole section of the specimen, thus offering the maximum resistance to the passage of current in the longitudinal direction ; (2) an ideal fibre or elongated structure with cementite as rods or streaks parallel to the longitudinal axis of the specimen, thus offering the minimum resistance in that direction ; (3) an ideal sorbitic structure with cementite as spherical particles in random distribution isotropically throughout the ferritic mass ; and (4) a ' chain structure ' in which spherical cementite particles in contact with one another are arranged in parallel rows along the direction of drawing.

For a 0·58% C steel, a change of structure from (1) to (2) can bring about a lowering in bulk resistivity by as much as 25%, whereas from (3) to (4) gives a decrease of only 0·9% (Section II). Structure (1) is intended as an analogy to a pearlitic structure and (2) represents the extreme limit of a fibre structure produced by drawing. In practice, however, there are a number of pearlite grains at random distribution and the cementite lamellae are not continuous across the whole section. The change from a pearlitic structure obtainable in practice to an ideal fibre structure as illustrated in (2), therefore, may not lower the bulk resistivity by more than half the value given above, *i.e.*, 12–13%. With regard to the ideal sorbitic structure assumed in (3), the main difference from practice is that the cementite particles in sorbite obtainable by heat-treatment are not spherical and therefore the effect of alignment of such particles into a ' chain structure ' described in (4) upon the change of bulk resistivity would be expected to be greater than 0·9%.

Bearing these factors in mind, the resistivity results may be examined in the light of change in cementite distribution brought about by drawing. Dealing first with lamellar cementite, in Section II are described three pearlitic structures for *D*1 (0·58% C), given by three different initial treatments, lead-patenting, normalizing, and annealing. On cold-drawing to 60–70% reduction where the fibre structure becomes pronounced, the lead-patented specimen shows an overall decrease in bulk resistivity of 5½%, measured in the longitudinal direction. The corresponding decrease for the normalized and annealed specimens is less, 4% and 1·8% respectively. These values of decrease in bulk resistivity are well within the limits given by the effect of change in cementite distribution brought about by drawing, as calculated above, even after allowing for the increase contributed by the cold-worked ferrite.

It has been stated in Section II that, after tempering a cold-drawn steel at about 600° C., the minimum resistivity observed is mainly due to the elongated distribution of cementite which remains. This is based on the fact that the general structure regarding the distribution of cementite is not altered to any appreciable extent up to 600° C., although the specimens are usually fully softened and the effect of cold-work in ferrite may be taken as completely removed. The difference between this minimum and the resistivity of the undrawn specimen may, therefore, be taken to indicate the decrease in resistivity due to the change of cementite distribution brought about by drawing. Referring again to *D*1, this difference is 6·3% for annealed pearlite (*see* Section II, p. 173) and 10% for normalized pearlite (add 4% to the minimum resistivity given in Fig. 40*a* (II)). These two values are nearer, but still within the calculated limit (12–13%). It should be noted, however, that cold-worked steels are prone to graphitization on subcritical annealing, and if commenced, this may contribute partly to the observed difference.

With regard to the change of cementite distribution in sorbite brought about by drawing, the observed decrease (1·4%) in the bulk resistivity of *D*1 at 70% reduction does not seem to agree very well with the calculated value (0·9%), since a certain amount of increase has to be allowed for the effect of cold-working on the ferrite. However, as already pointed out, the calculated value may be too low, largely because, in practice, the cementite particles in sorbite are not spherical. On subsequent annealing at 600° C., the minimum resistivity shown by the 70% reduction specimen is some 4½% lower than the resistivity of the undrawn specimen (Fig. 40*b* (II)). This difference may be too large to be accounted for by the effect of cementite distribution alone, and graphitization may play a part in lowering the bulk resistivity of the cold-drawn specimens on subcritical annealing.

Unlike cold-worked ingot iron, in which the resistivity decreases continuously with increasing tempering temperature up to 550–600° C. (Fig. 33*a* (II)), cold-worked high-carbon steels show a slight increase in resistivity on tempering at low temperatures with a maximum at 250–300° C. (Figs. 33*b*, 40*a*, and 40*b* (II)). Even at the maximum point, the increase is small, of the order of 0·1–0·2%. Bearing in mind the shape of the tempering-resistivity curve for the ingot iron *A*1, it seems that the increase in resistivity in cold-worked carbon steels on tempering actually covers a wide range of temperatures from 150° to about 450° C. The effect is more marked if the carbon content of the steel is higher, but there appears to be very little difference between cold-drawn pearlite and cold-drawn sorbite in the case of the 0·58% C steel *D*1 (Figs. 40*a* and 40*b* (II)). Since the increase in resistivity on tempering takes place in the same temperature range as the dilatation change—a permanent increase in length and contraction in diameter—there are two possible causes, *viz.*, the plastic yielding of the cementite, and the change of lattice spacings due to the release of macro-strains in the ferrite. As already discussed, on heating a cold-drawn steel wire, the cementite must deform plastically to allow the ferrite lattice to recover, to account for the observed dilatation effect. It is therefore possible that the small increase in the bulk resistivity of cold-drawn specimens on tempering is mainly contributed by the increase of resistivity in the cementite due to plastic deformation. In regard to the second possible cause, Uêda[44] found that with iron or carbon steels, elastic tension under external loading increases the resistivity of the specimens in the longitudinal direction. It is not known whether elastic compression will have a similar or opposite effect. If it has an opposite effect, then the recovery of the ferrite from compressive strains in the longitudinal direction in a cold-drawn steel wire on tempering may be partly responsible for the observed increase of resistivity. These explanations can also be applied to the resistivity results obtained on *CR*5 in which an inflexion showing a small increase in resistivity has been found on tempering at 350–400° C. only when the steel is cold-drawn from the Fe_3C condition (Fig. 33*c* (II)).

The correlation of the different properties of cold-worked steels with internal strains, as discussed above, shows that, in the past, whilst the effect of internal strains in ferrite is to some extent well known, the effect of such strains in cementite and of those due to mutual restraint between ferrite and cementite upon the bulk properties of cold-worked steels, has not been sufficiently realized.

The effect of cold-work upon hydrogen in steel has been investigated in connection with work on hair-line cracks. It is shown in Section VI that cold-working decreases the rate of hydrogen diffusion at room temperature, and the effect is similar for all steels irrespective of their carbon contents. The authors' view is that diffusion results obtained by electrolytic experiments are only qualitative. Whilst a change of lattice spacings can affect diffusion, the major contribution to the reduced rate of diffusion observed in cold-worked steels may be associated with the high hydrogen saturation, mainly in the form of occluded molecular hydrogen. With heat-treated steels, the results suggest that hydrogen diffusion at room temperature varies with the carbon content and is influenced by the state of division and distribution of the cementite present. For a given structure, a higher-carbon steel generally gives a lower rate of diffusion and, for a given steel, hydrogen diffusion appears to be less for a lamellar structure than if the cementite is present as broken segments or particles. With ingot iron in which ferrite is the only constituent, the hardness can be taken as a general indication of the rate of hydrogen diffusion; the lower the hardness, usually the higher will be the permeability for hydrogen. This is clearly indicated in Fig. 67 (VI), which shows that with cold-worked ingot-iron specimens the variation of hydrogen diffusion after tempering at different temperatures is directly opposite to the change of hardness.

The results in Section VI show that hydrogen saturation in steel also increases rapidly with cold-working. The increased saturation in cold-worked iron has been shown in a previous paper,[34] and it has been suggested that the hydrogen which could be introduced into iron or steel at room temperature by electrolytic treatment is accommodated in the speci-

men mainly in occluded form. The most likely place for the storage of such hydrogen is assumed to be the crystallite boundaries or mosaic disjunctions. As pointed out in Section VI, the variation in hydrogen saturation bears a certain relation with a change of hardness and density of the specimen. In a qualitative way, it may be said that an increase in hardness or a decrease in density will generally correspond with a higher hydrogen saturation. More specifically, there is a rather better correlation between X-ray line-broadening and hydrogen saturation. Thus, a comparison between Fig. 69*a* (VI) and Fig. 46*a* (III) will show that the correlation of hydrogen saturation with X-ray line-broadening is equally as good as with the hardness; the curves referred to in this case are those of *A*2, cold-drawn and tempered at different temperatures. With *D*2 (0·59% C), cold-drawn and tempered, both the hydrogen saturation and the X-ray line-broadening decrease with the tempering temperature almost right from the very beginning (Figs. 69*b* (VI) and 46*b* (III)), but the hardness of the specimen increases to a maximum at 300° C. and then decreases. In this case, at least, the hydrogen saturation agrees with the X-ray line-broadening, but not with the hardness.

With specimens in the as-drawn condition, the change of hardness follows that of X-ray line-broadening and, therefore, the correlation of hydrogen saturation with X-ray line-broadening is the same as with hardness. Such a correlation is good in the case of *D*2 (Fig. 68*b* (VI) and Fig. 47 (III)). With *A*2, however, the shape of the hydrogen saturation curve is somewhat different from that of the hardness curve (Fig. 68*a* (VI)), as well as that showing X-ray line-broadening for a similar steel (*A*3, Fig. 47 (III)), but it closely resembles the curve relating to the change of density with different drawing reductions (*A*1, Fig. 12 (I)). It should be noted that, with cold-drawn ingot iron or low-carbon steels, especially with a large specimen, there is a marked variation in macro-strains across the specimen section (Fig. 44*a* (III)). Whilst the X-ray line-broadening is based on measurements taken at the centre of the section, the hydrogen saturation, like the density, involves the specimen as a whole. The correlation between hydrogen saturation and X-ray line-broadening in cold-drawn and drawn and tempered steels, as discussed above, strongly supports the view that the hydrogen introduced by electrolytic treatment at room temperature is mainly accommodated in crystallite boundaries or mosaic disjunctions, as suggested in a previous paper.[34]

Acknowledgments

The authors thank their colleagues for their general interest and the help rendered during this investigation. They gratefully acknowledge financial aid from the British Iron and Steel Research Association, which has made it possible for the work to be extended. The results given in Section VI, which belong to a separate project at the instigation of B.I.S.R.A., have been reported from time to time to the Hair-Line Crack Sub-Committee, and the authors are indebted to the members for their interest and constructive criticism. Several of the investigators engaged in this work owe their gratitude to other sources, as follows: Hindu University, Benares, India (U. V. Bhat); Anglo-Chinese Education and Cultural Administration (P. L. Chang); British Council (B. Fang and R. Guenot); and the Andrew Carnegie Research Fund (R. Guenot).

References

1. G. I. TAYLOR : *Proceedings of the Royal Society*, 1934, series A, vol. 145, p. 362.
2. M. POLANYI : *Zeitschrift für Physik*, 1934, vol. 89, p. 660.
3. E. OROWAN : *Ibid.*, p. 634.
4. L. BRAGG : "Symposium on Internal Stresses in Metals and Alloys," p. 221. London, 1947 : Institute of Metals.
5. N. F. MOTT : *Ibid.*, p. 450.
6. A. T. ADAM : "Wire Drawing and the Cold Working of Steel." 2nd ed. London, 1936 : Witherby.
7. T. SWINDEN and G. R. BOLSOVER : *Journal of The Iron and Steel Institute*, 1927, No. I, p. 569.
8. J. H. ANDREW and H. LEE : *Ibid.*, 1942, No. I, p. 135P.
9. J. H. ANDREW and others : *Ibid.*, 1947, vol. 156, June, p. 208.
10. M. BALICKI : *Ibid.*, 1945, No. I, p. 181P.
11. N. P. ALLEN, W. T. GRIFFITHS, and L. B. PFEIL : *The Iron and Steel Institute*, 1939, *Special Report No.* 24, p. 369.
12. E. M. TRENT : *Journal of The Iron and Steel Institute*, 1941, No. I, p. 401P.
13–21 *See* p. 165, June issue.
22. G. KURDJUMOV and L. LYSSAK : *Ibid.*, 1947, vol. 156, May, p. 29.
23. R. D. HEIDENREICH and L. STURKY : *Journal of Applied Physics*, 1946, vol. 17, p. 127.
24–29. *See* p. 184, June issue.
30. W. A. WOOD : *Proceedings of the Royal Society*, 1948, series A, vol. 192, p. 218.
31. G. B. GREENOUGH : *Nature*, 1947, Aug. 23, p. 258.
32. C. ZENER and J. H. HOLLOMON : *Journal of Applied Physics*, 1944, vol. 15, p. 22.
33. B. E. WARREN : *Physical Review*, 1941, vol. 59, No. 9, p. 693.
34. J. H. ANDREW and H. LEE : "Symposium on Internal Stresses in Metals and Alloys," p. 265. London, 1947 : Institute of Metals.
35. G. BORELIUS and S. LINDBLOM : *Annalen der Physik*, 1927, vol. 82, p. 201.
36. C. A. EDWARDS : *Journal of The Iron and Steel Institute*, 1924, No. II, p. 9.
37. C. J. SMITHELLS and C. E. RANSLEY : *Proceedings of the Royal Society*, 1935, series A, vol. 150, p. 172.
38. P. GOERENS : *Journal of The Iron and Steel Institute*, 1911, No. 3, p. 320.
39. H. O'NEILL : "The Hardness of Metals and its Measurement." (1st Edn.). London, 1934 : Chapman and Hall, Ltd.
40. R. FORRER : *Journal de Physique et le Radium*, 1933, vol. 4, pp. 109 and 186.
41. E. C. STONER : "Magnetism and Matter." London, 1934 : Methuen and Co., Ltd.
42. K. H. JACK : *Nature*, 1946, vol. 158, July 13, p. 160.
43. F. WEVER and G. NAESER : *Mitteilungen aus dem Kaiser-Wilhelm-Institut für Eisenforschung zu Düsseldorf*, 1934, vol. 16, p. 201.
44. TARÔ UÊDA : *Science Reports of the Tôhoku Imperial University*, 1930, vol. 19, p. 473.

PROCEEDINGS OF
THE INSTITUTE

REPORTS OF COUNCIL - OFFICIAL NOTICES

AUTUMN GENERAL MEETING, 1949

THE AUTUMN MEETING OF THE IRON AND STEEL INSTITUTE was held on Thursday and Friday, 10th and 11th November, 1949, at the Offices of the Institute, 4 Grosvenor Gardens, London, S.W.1. The President, Sir ANDREW MCCANCE, LL.D., D.Sc., F.R.S., was in the chair on the first day and Dr. C. H. DESCH, F.R.S., Past-President, on the second day.

Sessions were held from 10.0 A.M. to 1.30 P.M. and from 2.30 P.M. to 6 P.M. on the Thursday, and from 10.0 A.M. to 1.15 P.M. and 2.30 P.M. to 5.0 P.M. on the Friday. On each day a buffet luncheon was provided in the Library of the Institute.

The Minutes of the previous meeting, held in London on 27th and 28th April, 1949, were taken as read and confirmed.

WELCOME TO MEMBERS AND VISITORS

The **President**: I am glad to have an opportunity to welcome the members and visitors to this Autumn Meeting. The Secretary reminds me that only a few days ago there occurred the fiftieth anniversary of the granting of our Charter, on 1st November, 1899. That is a long time, and I think that the Institute during that period has maintained steady and very effective progress. I think also that at no time in its previous history has the work been carried on with greater vigour.

AMENDMENTS TO BYE-LAWS

The **President**: Some amendments to the Bye-laws were approved at the Annual General Meeting last April, and I have to advise you that they have now been allowed by the Privy Council and have come into force. Their main effect is:

(1) To establish a class of Associate Members in place of the present class of Associates. The Council has prepared Regulations for the Associate Members, to come into effect on 1st January, 1950. These Regulations are very similar to those at present in force for Associates, and all Associates who are qualified, automatically become Associate Members. The Regulations will be published in the *Journal*.*

(2) To make compulsory the changes in subscriptions which have operated voluntarily since the beginning of this year. The Council is appreciative of the confidence shown in it by members in agreeing to pay the higher subscription rates before the legal procedure was completed.

FINANCE

The **President**: It will be more appropriate to deal with financial matters at the next Annual General Meeting, when the accounts for the present year will be presented; but I wish, on behalf of the Council, to assure you that great attention is being given to means of effecting further economies and increasing income. I think that there is every prospect of our operations this year resulting in a small surplus of income over expenditure, which is a very welcome change from the position in quite a number of previous years.

NOMINATION OF NEXT PRESIDENT

The **President**: I have pleasure in announcing, and I am sure that the members will be interested to learn, that the Council has unanimously decided to nominate Mr. J. R. Menzies-Wilson to be the next President. He will succeed me after the Annual General Meeting in 1950. I am sure that it will be your wish to extend to Mr. Menzies-Wilson our best wishes for the success of his tenure of office. (*Applause.*)

MEETINGS IN 1950

The **President**: The Annual General Meeting, 1950, will be held in London on Wednesday and Thursday, 26th and 27th April. There will be a Dinner for members on the evening of 27th April.

The Centenary of the death of Sidney Gilchrist Thomas falls on 16th April, 1950, and we have thought it right to commemorate that great man by a special Lecture. Mr. James Mitchell, our Honorary Treasurer, has agreed to deliver the Lecture on the evening of 26th April. I am sure that we could have made no better choice for this occasion.

We hope to arrange a Special Meeting to be held in Glasgow from 12th to 15th September, 1950. The details will be announced later.

We propose that the Autumn General Meeting shall again be held in London, as during recent years, the dates being Wednesday and Thursday, 15th and 16th November.

As previously announced, we are arranging to hold a Symposium on High Temperature Steels and Alloys for Gas Turbines in London on Wednesday and Thursday, 18th and 19th October, 1950. On the evening

* Published in the *Journal of The Iron and Steel Institute*, 1950, vol. 164, p. 92.

before, Air Commodore Sir Frank Whittle will give the Fifth Hatfield Memorial Lecture, on " The Development of the Gas Turbine and the Need for Special Steels and Alloys," a matter, I think, of very special interest to members.

THE JOURNAL

It may also interest members to hear that Sir Charles Goodeve, whom we welcome back after a long tour in the U.S.A. and Canada, has told us that the people whom he met in America all spoke very highly of the *Journal*. They think that it compares favourably with American publications. Unfortunately, the distribution in America is not as wide as we would wish, and we intend to take steps to increase the circulation, and if possible to increase the number of American members of the Institute. Suggestions to that end from members, and for increasing the usefulness and standing of the *Journal*, will always be welcomed by the Council.

CHANGES ON THE COUNCIL

The **Secretary** (Mr. K. Headlam-Morley) : I have to report the following changes on the Council since the last General Meeting, in April, 1949.

The following are Hon. Members of Council during their periods of office :

Mr. E. T. Judge, President of the Cleveland Institution of Engineers, in place of Mr. F. Shepherd.

Mr. R. C. Powell, President of the Ebbw Vale Metallurgical Society, in place of Mr. H. F. Padbury.

Mr. J. Wilkinson, President of the Leeds Metallurgical Society, in place of Mr. W. R. Berry.

Mr. E. Marks, President of the Staffordshire Iron and Steel Institute, in place of Mr. W. M. Larke.

Mr. Roosevelt Griffiths, President of the Swansea and District Metallurgical Society, in place of Mr. T. J. Canning.

Mr. W. Barr (who is also a Member of Council), President of the West of Scotland Iron and Steel Institute, in place of Mr. T. M. Service.

Mr. W. E. Bardgett, representing the Institution of Metallurgists, in place of Dr. J. E. Hurst.

The following are due to retire at the next Annual General Meeting and are eligible for re-election :

Vice-Presidents—Mr. W. B. Baxter, Mr. H. H. Burton, and Mr. R. Mather.

Members of Council—Professor J. H. Andrew, Mr. N. H. Rollason, Mr. R. A. Hacking, Mr. D. F. Campbell, and Mr. I. F. L. Elliot.

ANDREW CARNEGIE SCHOLARSHIPS

The **Secretary** : The following awards of Andrew Carnegie Scholarships have been made since the last General Meeting :

£125 to H. Föppl (Cambridge) for research on the evaluation of macroscopical residual stresses in elastic solids by measuring the strains and considering their relationship in the principal axes.

£50 to H. Ford (City and Guilds) for research on calculation method for roll force ; torque and mill power in cold strip rollings, with tensions applied to the strip.

£270 to C. Margaretha Hyden (Imatra, Finland ; to work at Sheffield) for research on the isothermal transformation of austenite.

£270 to N. H. Polakowski (University College, Swansea) for research on hot and cold deformation of steels and other metals.

BALLOT FOR THE ELECTION OF MEMBERS AND ASSOCIATES

Dr. J. H. CHESTERS (Rotherham) and Mr. T. ST. H. ACLAND (New Zealand), who had been appointed scrutineers of the ballot, reported that the following 81 Members and 45 Associates had been elected :

Members

Anderson, Johan Kristian L., Met.Eng. (Bergen, Norway) ; **Bacon,** Christopher Henry, B.A. (Shotton, Chester) ; **Bailey,** William, A.M.I.Mech.E. (Sheffield) ; **Binks,** Cornelius John (London) ; **Binks,** Oliver Frederick (London) ; **Bookey,** John Bernard, B.Sc., A.R.C.S. (London) ; **Bourdariat,** Marc (Apprieu (Isère), France) ; **Brown,** Kenneth MacMurray (Dunedin, New Zealand) ; **Campbell,** Denis, B.Sc., D.R.T.C. (Mossend, Lanarkshire) ; **Cartier Van Dissel,** Etienne Daniel (Utrecht, Holland) ; **Chander,** Soshil, B.Sc. (New York, U.S.A.) ; **Clayton-Cave,** Jack (London) ; **Cox,** Ernest Whitworth (Marrickville, N.S.W., Australia) ; **Croxford-Adams,** George Francis (Hunsbury, Northants.) ; **Cusworth,** William (Sheffield) ; **Cutler,** Percy (Ambarnath, near Bombay, India) ; **Dahl,** Verner Berg, B.Sc. (Elsinore, Denmark) ; **Dardel,** Yves Marie Pierre (Paris, France) ; **Dewhurst,** William (Sheffield) ; **Dhar,** Prem Ranjan, M.S.(Physics), M.S.(Met.) (New York, U.S.A.) ; **Dickens,** Arthur (Cardiff) ; **Dietrich,** Moritz Evelyn, A.I.M. (Vereeniging, Transvaal, South Africa) ; **Dunbar,** Alan Finlayson, B.Sc. (Melbourne, Victoria, Australia) ; **Escauriaza,** Jose Manuel (Las Arenas, Vizcaya, Spain) ; **Evers,** William (Widnes) ; **Fincham,** Christopher Joseph Barry, B.Sc. (London) ; **Flint,** George Arthur, B.Sc., G.I.Mech.E. (London) ; **Forrest,** Andrew Gillespie (Chicago, Ill., U.S.A.) ; **Garside,** F. C. (Sydney, N.S.W., Australia) ; **Gellner,** Otto Heinz, M.Sc. (London) ; **Gerrard,** James (Gateshead) ; **Gollin,** Geoffrey Joseph, M.I.Mech.E. (London) ; **Hadfield,** Douglas, M.A. (London) ; **Haenel,** João Gustavo (São Paulo, Brazil) ; **Hannant,** Vernon (Bishop Auckland) ; **Hay,** Alexander Taylor, A.I.M. (Radway Green, Cheshire) ; **Hiaváček,** Josef, Eng.M. (Kladno, Czechoslovakia) ; **Humphreys,** Oliver William, B.Sc., F.Inst.P., M.I.E.E. (Wembley) ; **Hynd,** Alexander (Leeds) ; **Kassem,** Mohamed A., Dr.Ing.Chem. (Chatby, Alexandria, Egypt) ; **Kornmüller,** Etmanno (Turin, Italy) ; **Krüger,** Christian Martin, D.Sc.(Eng.) (Pretoria, South Africa) ; **Lamb,** Hubert, A.M.C.T. (Manchester) ; **Langers,** Robert (Luxembourg) ; **Lee,** J. G. (London) ; **Luzuriaga,** Francisco (Pasajes, Guipuzcoa, Spain) ; **Madden,** Robert C., S.B. (Fontana, California, U.S.A.) ; **Mason,** Noel Henry, A.M.C.T., F.I.M. (London) ; **Mehra,** R. P. (Dooranda, Ranchi, India) ; **Mills,** Howard Robert, Ph.D., B.Sc., M.I.Mech.E. (London) ; **Moffatt,** Robert Sydney Martin, B.Sc.(Met.) (Scunthorpe) ; **Munnik,** Eric Howard (Que Que, Southern Rhodesia) ; **Newton,** James Welsby, B.Sc.(Eng.) (Stoke-on-Trent) ; **Ohman,** Einar (Stockholm, Sweden) ; **Orosco,** Eros (Rio de Janeiro, Brazil) ; **Patankar,** Muralidhar V., B.Sc.(Met.) (Bangalore, S. India) ; **Pattermann,** Otto (Pompey, France) ; **Peacock,** James Alfred, M.Inst.C.E. (Scunthorpe) ; **Pillans,** Charles Stuart Mortimer (Krugersdorp, Transvaal, South Africa) ; **Place,** Arthur (Sheffield) ; **Pollock,** Wallace Albert Charles, L.I.M. (Cardiff) ; **Rees,** R. W., B.Sc., F.I.M. (Nuffield Springs, Transvaal, South Africa) ; **Rivière,** Jaime (Mieres, Spain) ; **Ross,** Henry Urquhart, B.Eng., M.Sc. (Toronto, Canada) ; **Rowland,** John Minteith, A.S.T.C. (Waratah N.S.W., Australia) ; **Sharma,** N. K. Narayana, B.Sc.(Met.) (Burnpur, India) ; **Sharp,** Herbert John, B.Sc. (Greenford) ; **Shenton,** Edward Bertram (Smethwick) ; **Skinner,** Ernest Andrew (London) ; **Smith,** James Arthur, B.Met. (Stafford) ; **Speight,** Kenneth, Assoc.Met., L.I.M. (Sheffield) ; **Swan,** Albert William (Sheffield) ; **Taylor,** Abraham, Ph.D., M.Sc., F.Inst.P., F.I.M. (Birmingham) ; **Thompson,** Arthur Howard (Wolverhampton) ; **Timms,** William, B.Sc. (Langley, near Birmingham) ; **Valebjorg,** Per (Bergen, Norway) ; **van Ewijk,** Leopold Johan Gerard, Dr.Ir. (Vaassen, near Apeldoorn, Holland) ; **Ventafridda,** Vincenzo, Dott.Ing. (Bolzano, Italy) ; **Vroege,** Ir. Aart Kornelis (Ijmuiden, Holland) ; **Westman,** Ernest Sven Wentworth (London) ; **Zuithoff,** *Dr.* Ate Johannes (Utrecht, Holland).

Associates

Aisbitt, John Edward (Newcastle-on-Tyne) ; **Arnold,** Brian (Coventry) ; **Berry,** Brian Shepherd, B.Sc.(Met.) (Manchester) ; **Bigikocin,** Osman (London) ; **Binney,** Michael Francis, G.I.Mech.E. (Sheffield) ; **Brightman,** Kenneth Todd (Newcastle-on-Tyne) ; **Brown,** Benjamin Floyd, A.I.M.E. (Pittsburgh, Pa., U.S.A.) ; **Byer,** Kenneth George William (Malta, G.C.) ; **Cartwright,** Donald Roy (Liverpool) ; **Chalder,** Geoffrey (Newcastle-on-Tyne) ; **Cockle,** James Edwin Spencer,

G.I.Mech.E. (London); **Dagg,** Denys Ian (Newcastle-on-Tyne); **El-Mehairy,** Ahmed Ezzat, B.Sc.(Eng.) (London); **Giblin,** John Francis, B.Eng., L.I.M. (Prescot); **Green,** Terence Edwin (Manchester); **Gregory,** Peter (Farnborough, Hants.); **Gupta,** Suresh Chandra (Benares, (U.P.), India); **Hall,** John (Newcastle-on-Tyne); **Hawkins,** Neville (Manchester); **Hines,** John (Coventry); **Hoare,** Hubert Arthur, L.I.M. (Hatfield, Herts.); **Houseman,** David Henry, B.A. (Cambridge); **Keen,** Maureen Sheila Marie (Manchester); **McIntosh,** Peter Stewart (Newcastle-on-Tyne); **McKenzie,** James E. C., B.Eng. (Sheffield); **Mackenzie,** Margaret (Newcastle-on-Tyne); **Marshall,** J. B. (Preston); **Martin,** Alfred John (London); **Maund,** Owen Spencer, B.Eng. (Sheffield); **Mickleraith,** John, M.Sc. (Corby); **Miodownik,** Peter Alfred (London); **Pick,** John Julius, B.Eng.(Hons.Met.) (Greenford); **Poole,** David Michael (Manchester); **Rastogi,** Satish C. (Benares, India); **Rodgers,** Alan (Sheffield); **Rourke,** John Warren (London); **Ryder,** Colin David (Liverpool); **Sharma,** Harish Chandra (Benares, India); **Smith,** Kenneth Alfred (Wednesbury, Staffs.); **Sykes,** Geoffrey Victor (London); **Thickins,** John Beach, B.Sc.(Met.) (Corby); **Tweedy,** John Gordon (London); **Utteridge,** William Ronald (Coventry); **Waters,** Brian Harry Coles, B.A. (Cambridge); **White,** Douglas (Coventry).

The **President** said that these additions brought the total membership of the Institute to 4918.

PRESENTATION OF PAPERS

The following papers were presented and discussed (the date of publication is given in brackets):

Thursday, 10th November, 1949

Morning Session

"Open-Hearth Furnace Models." "Part I—Flow Patterns in Ducts," by J. H. Chesters and A. R. Philip. "Part II—Flow Visualization and Photography," by R. S. Howes and A. R. Philip. "Part III—Flow Patterns in Model Furnaces," by I. M. D. Halliday and A. R. Philip. (*August*, 1949).

"Experiments on Gaseous Mixing in Open-Hearth Furnace Models. Part I—Maerz," by R. D. Collins and J. D. Tyler. (*August*, 1949).

"Experiments on the Gas and Fluid Flow in a Side-Blown Converter Model," by M. P. Newby. (*August*, 1949).

Afternoon Session

"Mechanical Properties of Low-Carbon, Low-Alloy Steels containing Boron," by W. E. Bardgett and L. Reeve. (*November*, 1949).

"Further X-Ray Study of the Equilibrium Diagram of the Fe–Ni System," by E. A. Owen and Y. H. Liu. (*October*, 1949).

"Free Energy and Metastable States in the Fe–Ni and Fe–Mn Systems," by F. W. Jones and W. I. Pumphrey. (*October*, 1949).

"Microscopical Studies on the Iron–Nickel–Aluminium System. Part I—$\alpha + \beta$ Alloys and Isothermal Sections of the Phase Equilibrium Diagram," by A. J. Bradley. (*September*, 1949).

"Constitution of Iron–Nickel–Chromium Alloys at 650° to 800° C.," by W. P. Rees, B. D. Burns, and A. J. Cook. (*July*, 1949).

Friday, 11th November, 1949

Morning Session

"The Compression Test in Relation to Cold-Rolling," by N. H. Polakowski. (*November*, 1949).

"Change of Electrical Resistance during the Strain-Ageing of Iron," by A. H. Cottrell and A. T. Churchman. (*July*, 1949).

"Plastic Strain and Hysteresis in Drawn Steel Wire," by R. S. Brown. (*June*, 1949).

Afternoon Session

"Investigations on an Experimental Blast-Furnace," by H. L. Saunders, G. B. Butler, and J. M. Tweedy. (*October*, 1949).

"The Distribution of Materials in the Blast-Furnace. Part II—Compensated Charging," by H. L. Saunders and R. Wild. (*September*, 1949).

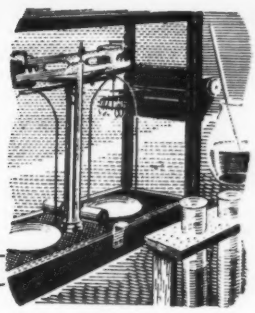
"Radio-active Technique to Determine Gas Velocities in a Driving Blast-Furnace," by E. W. Voice. (*November*, 1949).

"The Effect of Sodium Oxide Additions to Steelmaking Slags. Part I—Use of Soda to Dephosphorize Pig Iron at 1400° C.," by W. R. Maddocks and E. T. Turkdogan. (*July*, 1949).

Through pressure of space the publication of the reports of the discussion on papers must be deferred. It is hoped that they will appear in the September and October issues of the *Journal*.

B. I. S. R. A.

BRITISH IRON AND STEEL RESEARCH ASSOCIATION



The Use of the Oxygen Lance in British Electric Furnace Practice

FOREWORD

The use of gaseous oxygen to accelerate the refining process in steelmaking has probably made the most rapid progress among electric steelmakers, both in the U.S.A. and in Great Britain.

It was advocated by Bigge[1] in 1924 as an auxiliary tool for assisting the refining of steel in the electric furnace ; some two years later Browne[2] extended the original specification, in particular to the manufacture of silicon steels. The chemistry of the refining process is relatively simple ; the main function of the oxygen is to remove the carbon in the steels to the desired low level at a faster rate than is normally possible with the use of iron ore alone.

The use of the oxygen lance in the manufacture of stainless steel was the subject of a patent taken out by Chelius[3] in 1940. In this case the chemistry and economics of the oxygen-refining process are rather more complex, and temperature plays a very important rôle (*see* Part II, p. 415). Chelius specified the limits of temperature between which lancing was effective as 3000–3300° F. (1650–1820° C.). With oxygen it is possible to work a stainless heat at a temperature some 200° C. higher than normal, and carbon elimination and the recovery of chromium may be substantially improved, making the manufacture of stainless steel from all stainless scrap charges practicable. Without the use of oxygen the chromium loss to the slag, when refining all-stainless scrap charges, is so serious as to make the charge unworkable because of the very thick and heavy slag formed.

Although the use of the oxygen lance in steel refining in the electric furnace was proposed over 25 years ago, very little practical progress was made until after the end of World War II. In 1924 oxygen was probably considered to be too expensive, and the technique of handling bulk (liquid) oxygen was in its early stage of development, making the regular use of the lance a matter of considerable difficulty.

By the end of the war, the generation and transport of oxygen had greatly improved. The use of oxygen was widely developed in Germany for military purposes (*e.g.*, the V2 rocket bomb), and for various purposes in the steel industry. When Germany was defeated in 1945 the data were made available to Allied investigators.

Since 1945, numerous papers, mainly American, on the use of oxygen in the steel industry, have been published. Much of the experimental work has been reported by the American oxygen producers themselves, and the greater part has dealt with the use of oxygen in the open-hearth furnace. A report by Eisaman[4] describing the practice at the Carnegie Illinois Steel Corporation may probably be taken as representative of modern American practice in the use of the oxygen lance in electric furnaces. More recently Fischer[5] has described developments in Germany in the production of chrome steels with the help of the oxygen lance.

Contemporary British progress has not yet been widely reported, but although the British steel industry may have made a rather slower start in this field, it is certain that present-day practice is in no way inferior to that of American or Continental electric steelworks.

The Electric Process Sub-Committee of B.I.S.R.A. has had the subject under review since 1948, and during the past two years considerable progress has been made, both in theory

and in practice, and it is hoped that as the use of the oxygen lancing process becomes more widely adopted in the industry further reports will be published. This paper represents the first two major reports of practical experiences to be submitted to the Sub-Committee, and it will be appreciated that further experimental work is needed before the subject is fully understood, particularly in regard to the chemical mechanism of the use of the oxygen lance in stainless steel manufacture, and the methods of chromium recovery by reduction from the slag prior to tapping.

The paper is divided into two parts : Part I discusses the application of the oxygen lance to the refining of low-carbon steels not containing chromium, as practised at the works of Messrs. Brymbo Steelworks Ltd., Brymbo, Wrexham, and Part II deals with the production of 18/8 stainless steels with the oxygen lance at Messrs. Edgar Allen and Co., Ltd., Imperial Steelworks, Sheffield.

Part I—THE USE OF OXYGEN FOR THE PRODUCTION OF LOW-CARBON ALLOY STEELS OTHER THAN HIGH-CHROME STEELS*

By T. H. Harris, A.Met., and D. J. O. Brandt, A.R.S.M., B.Sc., A.I.M.

SYNOPSIS

The technique of using the oxygen lance during the boiling-down period in 18-ton and 29-ton electric arc furnaces is described.

Typical results obtained on both high-carbon and low-carbon charges are recorded in tables, and graphs are given showing that the rate of carbon removal and the effectiveness of the oxygen lance diminish as the carbon in the bath falls.

The effect of oxygen on residual manganese is discussed ; data giving the possible rise in temperature during oxygen injection and some records of lance life are included.

It is concluded that for successful operation a ' specific oxygen input rate ' of more than 5 cu. ft./min. per ton of steel must be used.

Introduction

In the summer of 1948, the Brymbo Steelworks became actively interested in the possibilities of increasing the production of steel by shortening the refining period, and encouraging results were obtained using the air lance in the open-hearth plant.

This successful application of compressed air to the open-hearth steelmaking process led to the possibility of its use in the electric plant, and initial trials with the air lance were carried out. The results were negative and indicated that if the removal of carbon was to be accelerated, oxygen would be necessary.

The oxygen line, of 1-in. internal dia. copper piping with some $\frac{11}{16}$-in. sections, from the liquid oxygen evaporator unit installed for scrap cutting and ingot deseaming, was therefore extended to the electric furnaces and initial trials were conducted at night when the consumption of oxygen for other purposes had ceased, and a maximum flow of about 150 cu. ft./min. was available. $\frac{1}{2}$-in. and $\frac{3}{4}$-in. dia. lances were immersed in the bath.

Initial results showed that the removal of both carbon and manganese was slow and uncertain and that lance consumption was high. Rather more promising results were obtained when the oxygen was blown into the slag, the end of the lance being held above the slag/metal interface.

Further trials with increased oxygen flow were carried out in collaboration with the British Oxygen Co., Ltd. A welded steel pipeline of $1\frac{1}{2}$ in. internal dia. was laid from the liquid oxygen plant to the electric melting shop, and the storage and evaporating capacity in the oxygen plant was increased.

A pressure regulator was fitted in the new line—designed to reduce the normal line pressure of about 250 lb./sq. in. to a constant 150 lb./sq. in. at the furnaces—and an orifice plate and flow meter were incorporated for metering the oxygen used. But pressure variations during blowing gave unreliable manometer readings, and the pressure regulator seriously reduced the rate of oxygen flow. It was therefore taken out and, to give a more manageable pressure at the furnaces, the working pressure at the oxygen house was reduced to 200 lb./sq. in. Oxygen blowing was carried out for some weeks under these conditions, and when the general technique was well established the pressure at the oxygen house was increased to the standard 250 lb./sq. in.

This resulted in an oxygen flow of over 400 cu. ft./min. being available at the furnaces, and under these conditions the use of oxygen has been adopted as a regular practice in the making of some steels.

STEELMAKING PRACTICE AT BRYMBO

The steelmaking practice for the production of certain types of low-carbon alloy steel in the electric melting shop at Brymbo is particularly well suited to the use of the oxygen lance, since it is usual for the heat to be deliberately melted out at a relatively high carbon content. The bath is then subjected to a prolonged boil with a view to obtaining a clean steel in the finished product, and thus the refining

Paper SM/AC/20/50 of the Electric Process Sub-Committee of the Steelmaking Division of the British Iron and Steel Research Association, received 27th March, 1950. The views expressed are the authors' and are not necessarily endorsed by the Sub-Committee as a body.

Mr. Harris is on the staff of Brymbo Steelworks, Ltd.

Mr. Brandt is a Senior Scientific Officer in the Steelmaking Division of the Association.

period takes up a considerable proportion of the total heat time, and the faster carbon elimination, possible when oxygen is used, is of great value.

The examination of the effects of oxygen lancing on the carbon content of steels has been divided into two sets of results ; those starting from a high carbon content (about 0·30–0·80%) and those starting with the carbon already below 0·12%.

Furnaces—The electric furnace plant at Brymbo consists of three Siemens Schuckert arc furnaces of the run-out shell type, of 14 ft. shell dia., and a nominal capacity of 15 tons each, the transformer ratings being 7500 kVA.

The standard charge weight was originally 18–19 tons, with a bath 1 ft. 9 in. deep and 10 ft. dia. at sill level. The capacity of these units has now been increased to 29–30 tons by alterations to the hearth contour. The larger capacity bath has a depth of 2 ft. 3 in., and a 10 ft. 9 in. dia. at sill level. During the period covered by this report one of the furnaces operated for some weeks with the original bath contour, thus the effects of oxygen blowing on both 29-ton and 18-ton charges have been studied.

The normal refractory lining is made up of a graphitized 'doloma' hearth, semi-stable dolomite brick sidewalls, and a 14-in. silica roof.

Oxygen Lancing Operation

Hose Connections and Lances—From the main $1\frac{1}{2}$-in. welded steel pipe line carried along the side of the shop adjoining the furnaces, $1\frac{1}{2}$-in. branch pipes lead down to the furnaces. A main gas cock and pressure gauge are fitted at the end of each branch pipe. From this a length of $1\frac{5}{8}$-in. armoured rubber hose leads to a **Y**-piece made up of $1\frac{1}{4}$-in. steam pipe, and further lengths of $1\frac{5}{8}$-in. hose conduct the oxygen from the arms of the **Y**-piece to lengths of $1\frac{1}{4}$-in. piping which carry reducing sockets into which

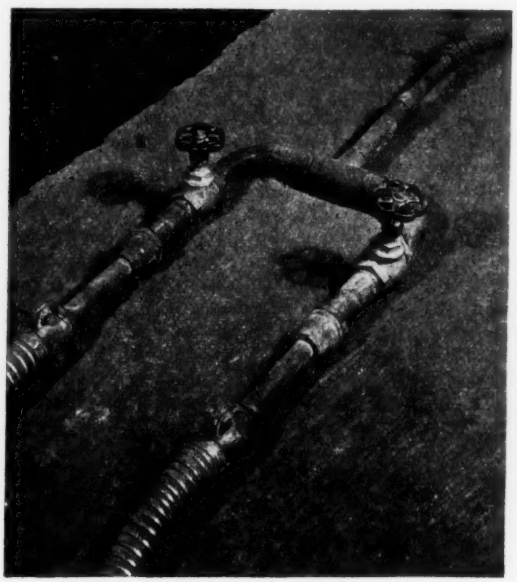


Fig. 1—Y-piece showing clamps for connecting armoured hose at Brymbo

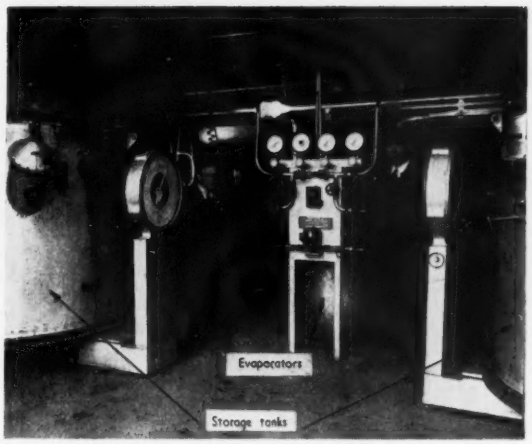


Fig. 2—Oxygen evaporating plant showing storage tanks, evaporators, weighing machines, and control panel

the lances are screwed. The hoses are held by stout screw clamps, and the whole arrangement can withstand a pressure of 200 lb./sq. in. or more (*see* Fig. 1).

Between the main pipe and the lance there is no pressure-reducing constriction with lances up to $1\frac{1}{4}$ in., and the pressure gauge on the branch pipe may be taken as giving a reading very close to the actual pressure at the inlet of the lance when the gas cocks are full open. Armoured hose of $1\frac{3}{4}$-in. bore and a **Y**-piece made up of $1\frac{1}{2}$-in. gas pipe is kept in reserve for use with lances larger than $1\frac{1}{4}$ in.

The **Y**-piece was originally fitted to cut out delays when changing lances ; a new lance was fitted to one branch of the **Y** while blowing through the other branch. This arrangement was later found useful when small-bore lances only were available and when the total oxygen flow was increased by using two lances in parallel.

Lances of $\frac{3}{8}$-in.–$1\frac{1}{2}$-in. bore have been used, depending on the size most readily available. In general, $\frac{3}{4}$-in. steam piping has proved the most suitable. Sizes as small as $\frac{3}{8}$ in. restrict the oxygen flow even when used in parallel and tend to break owing to weakness at the threaded ends. The life of the lance tends to decrease with bores larger than 1 in., because of the lower velocity and consequent decreased cooling effect of the oxygen. Thicker walled hydraulic piping of $\frac{5}{8}$-in.–$1\frac{1}{2}$-in. bore has showed no apparent advantages over steam piping.

Metering the Oxygen—The arrangement of an orifice plate and manometer in the main pipe line to assess the volume of oxygen passed into the furnace was unsatisfactory.

The oxygen evaporator plant contains two liquid oxygen storage tanks of 47,000 cu. ft. (*i.e.*, 47,000 cu. ft. of oxygen gas at N.T.P.) capacity on weighing machines fitted with scales giving readings in cu. ft. (*see* Fig. 2). For convenience of recharging, the oxygen for the furnaces and for general works' use is drawn from one tank, through two separate lines ; one tank is refilled and held in reserve while the other is in use. A positive displacement meter, suitable for relatively small flows, is fitted in the works' line, but

Fig. 3—Commencement of blowing on a 15-ton Siemens Shuckert furnace

the normal rate of flow in the furnace line is too high for this type of meter.

The storage-tank weight and the meter are read at the beginning and end of each blow and the total used, less the works' consumption as calculated from the meter readings, is taken as the amount used for the blow. The amounts recorded are susceptible to errors arising from :

(1) Time differences between tank weighings, meter readings, and the actual blowing

(2) Pressure variations during blowing. (The meter readings are multiplied by a factor corresponding to the average pressure during the blow)

(3) Evaporation losses and leaks.

The arrangement is not ideal, but the results indicate that errors are small and probably fairly constant from blow to blow.

Blowing Operation—As an example, the normal method of blowing a 29-ton heat melting at 0·50–0·60% of C is as follows :

The lances ($\frac{3}{4}$ in. for preference) are connected to the flexible hose fittings described above. It is usual to screw any short lengths of piping, of the same diameter left over from a previous blow on to the ends of the standard 20–21-ft. lengths.

After a bath sample has been drawn and a temperature taken by the immersion pyrometer, a shield of $\frac{5}{8}$-in. plate about 5 ft. × 7 ft. is placed about 3 ft. in front of the door (*see* Fig. 3). A lance is passed through the slot in the shield and the main cock on the wall pipe is opened slightly, the cock on the branch of the **Y**-piece leading to the lance being full open. (The cock on the wall pipe is used throughout for controlling the oxygen flow to avoid subjecting the hose connection to the full-line pressure of 250 lb./sq. in.)

With a reduced oxygen flow the end of the lance is well coated with slag and the flow is then gradually increased to the full rate. The end of the lance is dipped in the slag just above the slag/metal interface and about 2 ft. 6 in. from the breast. Thick brown fumes are evolved indicating the direct oxidation of iron, bath temperature and iron oxide concentration increase, and the bath boils vigorously, the iron oxide fumes being gradually replaced by the carbon flame. Careful control of the oxygen injection is needed at this early stage since the violence of the carbon oxidation may cause slag and metal to boil over the sill, particularly if the bottom layer of the metal bath is colder than the surface layers ; this may occur if there is any delay during the melting of the charge causing 'setting back,' or it may occur on the first heat of the week.

As the lance is consumed it is moved slowly forward. When blowing down from a medium or high carbon the frothing slag provides a good insulating cover for the lance and may last for 30 min. or more. If necessary, the boil is controlled by reducing the oxygen flow and by withdrawing the lance for short intervals.

The carbon content of the bath can be estimated roughly from the appearance of the flame and slag, and if necessary blowing is continued with a second or a third lance. 'Fracture' samples are usually drawn at the same time as bath samples, for rather more accurate estimation of the carbon.

Provided the manganese, chromium, and phosphorus contents of the iron and the specification allow, the most economical way of using oxygen is to run the carbon down from the melt to the desired figure in one operation without intermediate slagging or sampling.

When a particularly low carbon is required or when the first blow has failed to remove the carbon to the desired point, or after slagging and building up of a fresh slag bulk, further oxygen injection is carried out at a lower starting carbon content. Rather more care is required at this stage as the rapid increase in the iron oxide content of the slag can cause pronounced erosion of the slag line. The rate of carbon oxidation at this stage is much slower.

It is not always possible to draw bath samples immediately after a blow ; time has to be allowed for the boil to subside, and, with medium- and high-carbon contents, for the flame to drop.

The refining, or 'boiling,' action continues at a considerable rate for some time after the lance is withdrawn, but the reaction is probably a little slower than when the gas is actually flowing. The 'refining speed' can be calculated only from the carbon difference between two samples, giving the mean rate of carbon removal only in the period between the times the two samples were drawn. The actual average refining speed during the passage of oxygen may have been a little higher than the results show. Similarly, the figures for specific consumption during blowing may be a little lower than those given. From the practical steelmakers' point of view this is, of course, immaterial.

CHEMISTRY OF REFINING PROCESS

Reduction of Bath Carbon with Oxygen

Within the limits of accuracy due to the practical difficulties already mentioned—the method of meter-

Table Ia—18-TON HEATS : REMOVAL OF CARBON FROM ABOVE 0·13%

Table Ia—18-TON HEATS : REMOVAL OF CARBON FROM ABOVE 0·13%

Heat No.	Bath Carbon		Time Between Samples, min.	Rate of Carbon Removal, %/hr.	Lances Used		Lance Pressure, lb./sq. in.	Volume Oxygen Blown, cu. ft.	Blowing Time, min.	Blowing Rate, cu. ft./min.	Bath Temperature		Specific Oxygen Input, cu. ft./min./ton	Specific Consumption, cu. ft./pt. C/ton
	Before Blowing, %	After Blowing, %			No. of 20-ft. Pipes	Dia., in.					Before Blowing, °C.	After Blowing, °C.		
1	0·14	0·045	25	0·23	1		140	2610	12	217	1570	...	12·0	15·3
2	0·70	0·04	50	0·79	1		80	9420	31	304	1470	1660	16·9	7·9
3	0·33	0·045	64	0·265	4		130	6830	32	214	1620	...	11·9	12·8
4	0·48	0·05	27	0·95	2*		105	6960	18	387	1515	1640	21·4	9·0
5	0·38	0·06	20	0·96	2*		115	4480	15	299	1532	1600	16·6	7·8
6	0·41	0·055	36	0·61	2*		140	7580	24	316	1520	1590	17·5	11·5
7	0·70	0·055	55	0·70	2*		...	7520	35	215	1490	1535	11·9	6·5
8	0·14	0·06	25	0·19	2*		...	2890	15	193	1530	...	10·7	20·0
9	0·98	0·045	90	0·62	6*		120	12,210	48	255	1500	1540	14·2	7·2
10	0·31	0·08	35	0·40	2*		140	5160	19	270	1520	1605	15·0	12·5
11	0·64	0·05	32	0·17	2*		150	3620	13	278	1540	1570	15·5	28·8
12	0·60	0·045	75	0·445	2*		140	7440	36	207	1510	1608	11·5	6·7
13	0·94	0·04	95	0·57	2*		150	14,210	53	274	1530	1660	15·2	8·8
14	0·45	0·075	30	0·75	2*		130	4580	13	339	1580	1605†	18·8	7·0
15	0·77	0·05	85	0·51	1		130	12,330	47	263	1510	1605	14·6	9·6
16	0·78	0·05	45	0·93	1		120	8700	29	300	1550	1644†	16·7	6·9
17	0·98	0·04	91	0·49	2		150	13,580	45	302	1520	1680	16·8	10·1
18	0·52	0·045	84	0·68	2		150	12,660	40	300	1515	1620	17·1	7·5
19	0·70	0·045	69	0·41	1		190	7950	24	330	1525	1648	18·3	9·3
20	0·70	0·09	60	0·73	1		200	6650	23	288	1510	1625	16·0	6·1
21	0·75	0·045	51	0·85	1		75	8540	23	371	1480	1600	20·6	6·8
22	0·25	0·06	60	0·21	2*		120	4260	22	194	1522	1570	10·7	12·4

* Two lances used in parallel
† 6 cwt. of scrap added

ing the oxygen and the delay between the completion of injection and sampling the bath—an attempt has been made to assess the general effectiveness of the oxygen lance for removing carbon from the electric furnace bath at various carbon levels.

The results do not take into account the oxidation of manganese and silicon remaining in the steel at melt-out. Manganese normally melts out at between 0·40% and 0·55%, but since the oxygen equivalent of manganese is very much lower than that of carbon, the amount of oxygen used in the production of manganese oxide is comparatively small and may reasonably be neglected.

Silicon, apart from exceptional cases, normally melts-out at very low figures and silicon analyses are not made on the bath samples drawn during the boil. High-chromium steels are not produced at the Brymbo Steelworks.

Tables I, II, III, and IV show the effect of a single blow, either long or short, fast or slow, on the carbon content of a bath of metal at various temperatures and at various stages of decarburization for 18-ton and 29-ton heats in the high- and low-carbon ranges. All details of carbon content, sampling times, blowing times, blowing rates, pressures, temperatures, and lances used are included in these tables. The delay between blowing time and sampling time is unavoidable in practice because of the normal exigencies of a production shop, but the examples have been selected so that so far as possible the amount by which sampling time exceeds blowing time is similar in each case.

The specific oxygen input figure represents the volume of oxygen injected per min. per ton of steel in the bath during blowing, and specific consumption is the volume of oxygen used to remove 0·01% of carbon (or 1 point of carbon) per ton of steel in the bath.

The values of mean rate of decarburization and specific consumption have been plotted against different values of initial carbon content, and the results are shown graphically in Figs. 4, 5, 6, and 7. The points plotted represent the mean rate at which the carbon was removed, or oxygen consumed, between the initial carbon content and the final carbon content of 0·04–0·05%. From a research standpoint this figure has little value, but from it the practical steelmaker can readily calculate the time, and the

Table Ib

ORE HEATS : REMOVAL OF CARBON FROM ABOVE 0·13%

Heat No.	Bath Carbon		Rate of Carbon Removal, %/hr.
	First Sample, %	Second Sample, %	
O1	0·50	0·22	0·20
	0·22	0·14	0·11
O2	0·70	0·43	0·27
	0·43	0·30	0·31
O3	0·82	0·61	0·135
O4	0·70	0·48	0·15
O5	0·60	0·30	0·19

Table II*a*—29-TON HEATS : REMOVAL OF CARBON FROM ABOVE 0·13%

Heat No.	Bath Carbon		Time Between Samples, min.	Rate of Carbon Removal, %/hr.	Lances Used		Lance Pressure, lb./sq. in.	Volume Oxygen Blown, cu. ft.	Blowing Time, min.	Blowing Rate, cu. ft./min.	Bath Temperature		Specific Oxygen Input, cu. ft./min./ton	Specific Consumption, cu. ft./pt. C/ton
	Before Blowing, %	After Blowing, %			No. of 20-ft. Pipes	Dia., in.					Before Blowing, °C.	After Blowing, °C.		
23	0·35	0·045	37	0·52	2	1½	75	8870	24	370	..	1550	12·7	7·4
					1	1½	100							
24	0·39	0·07	40	0·48	1	1½	75	6650	22	302	1572	1600	10·4	7·2
25	0·29	0·035	38	0·405	1	1½	..	4890	21	245	1530	..	8·4	7·6
26	0·45	0·07	56	0·405	1	1½	125	7940	37	215	1520	1580	7·4	7·2
27	0·51	0·045	44	0·50	3	1½	..	9210	33	279	1520	1610	9·6	7·8
28	0·44	0·045	60	0·395	2	1½	75	9380	36	261	1540	1560	9·0	8·2
29	0·43	0·075	50	0·425	1	1½	..	9500	27	362	1565	1600	12·5	9·5
30	0·43	0·09	50	0·41	1	1½	..	9310	37	252	1515	1565	8·7	9·4
31	0·24	0·05	30	0·38	1	1½	140	4300	12	365	1520	1530	12·6	7·8
32	0·38	0·065	55	0·345	2	1½	90	8220	27	304	1520	..	10·5	9·0
33	0·25	0·06	22	0·52	1	1½	80	3810	13	293	1540	1565	10·1	6·9
34	0·44	0·075	40	0·55	1	1½	75	10,130	30	338	1515	1585	13·4	9·5
35	0·14	0·04	25	0·24	2	1	115	5410	17	318	1520	..	11·0	18·6
36	0·13	0·06	30	0·14	2	1	70	3630	14	278	1555	..	9·6	17·8
37	0·75	0·04	77	0·55	4	1	110	16,500	44	384	1540	1710	13·2	8·0
38	0·50	0·11	50	0·47	2	1	90	6380	20	319	1515	1565	11·0	5·6
39	0·70	0·045	70	0·36	3	1	75	13,930	45	310	..	1585	10·7	7·4
40	0·52	0·04	80	0·36	2*	..	..	13,650	45	303	..	1610	11·6	10·9
41	0·50	0·055	60	0·44	2*	..	..	8860	29	295	1510	1580	11·4	7·7
42	0·25	0·05	25	0·48	2*	..	160	6410	20	320	1520	1582	11·0	11·0
43	0·15	0·06	12	0·45	..	..	100	2610	8	326	..	1520	11·3	10·0
44	0·23	0·06	20	0·51	1	1	70	4850	13	373	..	..	12·8	9·9

* Two lances used in parallel

volume of oxygen, required to complete the refining process.

By plotting the mean rates of carbon elimination against the mean carbon contents *between* each sample, a curve which is of greater interest to the research worker may be obtained. The dotted lines in Figs. 4, 5, 6, and 7 show the probable actual rate of carbon elimination and oxygen usage which will take place at any given carbon content during the course of blowing.

Carbon Content and Rate of Carbon Elimination—Figures 4*a* and *b* illustrate how the rate of carbon elimination under oxygen injection falls as the carbon content of the metal falls, and show the effect of the different specific oxygen inputs obtained with the two different sizes of furnace. The results for the 18-ton furnace show a greater degree of scatter than those for the 29-ton unit, possibly owing to the wider range of oxygen input on the smaller charge.

The two full-line curves for mean decarburization rate against initial carbon, and the derived (dotted) curves for rate of elimination against actual carbon, show that in the case of the 29-ton furnace the maximum rate of elimination compatible with an oxygen input of 8–13 cu. ft./ton/min. is between 40 and 50 points/hr., and that in amounts above 0·20% the bath carbon is sufficiently 'active' for this rate to be maintained. In the 18-ton furnace (taking the derived curve) the rate of elimination at 0·20% of C is also approx. 40 points/hr., but when the carbon has reached the 'activity' equivalent to a content of over 0·40% the increased specific oxygen input on this furnace enables the rate of elimination to be raised to a maximum figure of some 70–80 points/hr. In terms of weight of carbon removed, this is equivalent to 260–325 lb./hr. and 280–320 lb./hr., corresponding to an actual oxygen input of about 300 cu. ft./min. in each case.

On the 18-ton heats the boiling time for a charge melting-out under 0·70% of C will amount to roughly 1 hr. ; on the 29-ton furnace a charge under 0·40% of C at melt-out can be boiled down in about 1 hr., a charge melting-out at 0·70% of C requiring about 1½ hr. For heats boiled with ore and melting-out at 0·60% of C on either furnace the time taken to remove the carbon will be roughly 3 hr.

Table II*b*

ORE HEATS : REMOVAL OF CARBON FROM ABOVE 0·13%

Heat No.	Bath Carbon		Rate of Carbon Removal, %/hr.
	First Sample, %	Second Sample, %	
O 6	0·50	0·24	0·21
O 7	0·70	0·38	0·16
O 8	0·50	0·30	0·125
O 9	0·70	0·30	0·25
O10	0·56	0·21	0·28
O11	0·50	0·71	0·125
O12	0·60	0·12	0·175
O13	0·31	0·25	0·12

Carbon Content and Consumption of Oxygen—The curves, Figs. 5*a* and *b*, show how the consumption of oxygen for every 'point' (0·01%) of carbon eliminated from every ton of steel in the bath increases as the carbon content of the bath drops, *i.e.*, as the 'activity' of the carbon becomes less. The scatter in Fig. 5*a* (the 18-ton heats) is considerably less than that in Fig. 4*a*.

Figure 5 confirms the indications apparent in Fig. 4. In the 29-ton furnace the 'efficiency' of oxygen usage remains constant at about 7–8 cu. ft./point of carbon/ton steel so long as the carbon content of the steel is above 0·20%. Below this figure the 'activity' of the carbon is so reduced that at an oxygen input of 8–13 cu. ft./ton/min. the effectiveness of the oxygen falls off; the reaction cannot keep pace with the speed at which the oxygen wants to force it. With the higher oxygen input the activity of carbon in the 18-ton furnace has been lowered sufficiently at 0·40% of C to check the reaction speed, and the specific consumption begins to drop. Provided that the carbon content of the steel is so high that the chemical reaction between carbon and oxygen can keep pace with the rate of oxygen input, then the specific oxygen consumption in both the large and the small furnaces remains constant at about 7·5 cu. ft./point of carbon/ton of steel. This figure is, of course, subject to the possible errors already mentioned.

Theoretically the removal of 0·01% of C from a ton of steel would require 3·2 cu. ft. of oxygen for conversion to carbon monoxide and 6·4 cu. ft. for conversion to carbon dioxide.

Figure 4*b* shows that a specific input of about 10 cu. ft./ton/min. will give a carbon elimination of about 40 points/hr. (provided the bath carbon is high enough) and Fig. 4*a* shows that an input of about 15 cu. ft./ton/min. gives an elimination of 60–70 points/hr. In the early trials only 150 cu. ft./min. of oxygen was available, giving a specific input of approx. 5 cu. ft./ton/min. on a 29-ton heat. At this input an elimination of about 20 points/hr. is all that can be reasonably expected—no more in fact than is obtainable with iron ore—and explains the failure of the early test.

With a large amount of carbon in the bath higher rates of oxygen input could be expected to give increased rates of carbon removal. Table I shows that at rates of input of 17–21 cu. ft. of oxygen/ton/min., eliminations of 93–96 points of carbon/hr. have been recorded. In practice, however, the difficulty of controlling a vigorous boil without loss of metal and slag over the sill, and the excessive rise in bath temperature, limit the rate of carbon removal.

Results at Low Carbon Contents—Figures 6 and 7 show the refining speed and specific consumption for low-carbon heats, in the same manner as Figs. 4 and 5, the scales being suitably expanded to cover the smaller carbon range. In Fig. 7 the oxygen consumption ordinate is plotted on a logarithmic scale.

Figure 6 shows that although in these ranges there is little difference between the rates of carbon removal in the two furnaces, the removal in the 18-ton furnace is definitely a little faster.

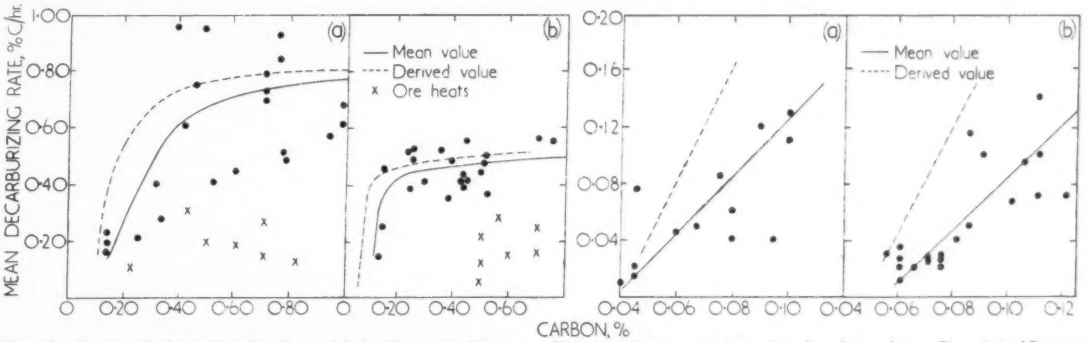


Fig. 4—Rate of decarburization (high C) : (*a*) 18-ton furnace (10–20 cu. ft. ton min.), (*b*) 29-ton furnace (8–13 cu. ft./ton min.)

Fig. 6—Rate of decarburization (low C) : (*a*) 18-ton furnace (11–25 cu. ft./ton min.), (*b*) 29-ton furnace (8–14 cu. ft. ton min.)

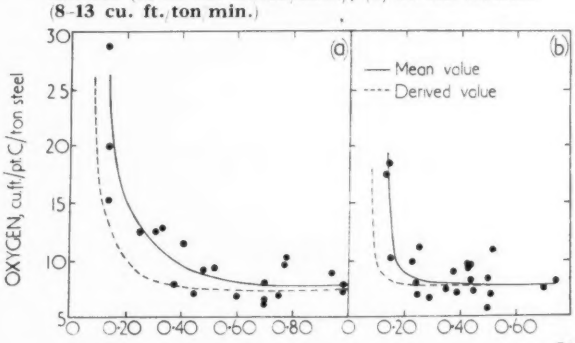


Fig. 5—Specific consumption (high C) : (*a*) 18-ton furnace, (*b*) 29-ton furnace

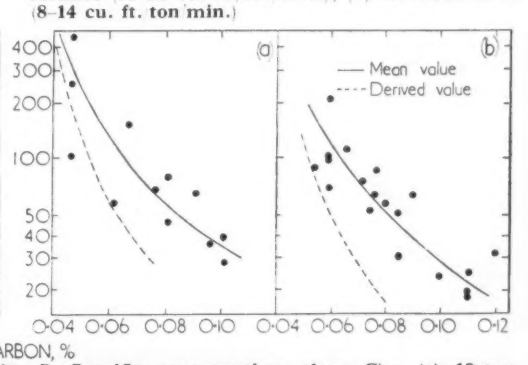


Fig. 7—Specific consumption (low C) : (*a*) 18-ton furnace, (*b*) 29-ton furnace

Table III

18-TON HEATS : REMOVAL OF CARBON BELOW 0·12%

Heat No.	Bath Carbon		Time Between Samples, min.	Rate of Carbon Removal, %/hr.	Lances Used		Lance Pressure, lb./sq. in.	Volume Oxygen Blown, cu. ft.	Blowing Time, min.	Blowing Rate, cu. ft./min.	Bath Temperature		Specific Oxygen Input, cu. ft./min./ton	Specific Consumption, cu. ft./pt. C/ton
	Before Blowing, %	After Blowing, %			No. of 20-ft. Pipes	Dia., in.					Before Blowing, °C.	After Blowing, °C.		
45	0·06	0·04	27	0·045	2*		105	2120	10	212	1590	1680	11·8	59
46	0·08	0·04	40	0·06	4*		140	5800	30	193	1560	1600	10·7	81
47	0·08	0·04	60	0·04	2*		140	3220	15	215	1555	1590	12·0	45
48	0·095	0·045	60	0·04	4*		100	2650	13	204	1552	1585	11·3	30
49	0·075	0·04	25	0·085	2*		150	4350	10	435	1605	1625	24·1	69
50	0·10	0·045	30	0·11	2*		...	2830	6	470	1532	1564	26·1	29
51	0·065	0·04	30	0·05	2		110	7100	19	373	1625	1648	20·7	156
52	0·045	0·035	8	0·075	...		...	1840	4½	410	1655	1660	22·8	102
53	0·045	0·04	15	0·02	1		110	3950	9	438	...	1630	24·4	440
54	0·04	0·035	30	0·01	1		120	8200	21	390	1600	1660	21·7	910
55	0·09	0·05	20	0·12	1		120	4600	16	288	1625	1665	16·0	64
56	0·045	0·04	20	0·015	2*		150	2350	10	235	1600	1580	13·1	261
57	0·10	0·055	20	0·13	2*		180	3180	9	354	1615	1630	19·7	394

* Two lances used in parallel

Table IV

29-TON HEATS : REMOVAL OF CARBON BELOW 0·12%

Heat No.	Bath Carbon		Time Between Samples, min.	Rate of Carbon Removal, %/hr.	Lances Used		Lance Pressure, lb./sq. in.	Volume Oxygen Blown, cu. ft.	Blowing Time, min.	Blowing Rate, cu. ft./min.	Bath Temperature		Specific Oxygen Input, cu. ft./min./ton	Specific Consumption, cu. ft./pt. C/ton
	Before Blowing, %	After Blowing, %			No. of 20-ft. Pipes	Dia., in.					Before Blowing, °C.	After Blowing, °C.		
58	0·11	0·06	30	0·10	1	1¼	80	2890	9	320	...	...	11·0	20
59	0·11	0·06	43	0·07	2	1¼	50	3820	14	276	...	...	9·5	26
60	0·07	0·05	48	0·025	1	1¼	135	4600	15	307	1600	...	10·7	79
61	0·075	0·05	60	0·025	1	1	135	5660	18	314	...	...	10·8	88
62	0·065	0·055	30	0·02	1	1	120	3480	14	248	...	...	8·5	120
63	0·075	0·045	90	0·02	1	1	...	5720	20	286	1600	1610	9·9	66
64	0·07	0·045	60	0·025	1	1	100	2130	15	140	...	...	4·8	29
65	0·08	0·065	23	0·04	¾	1	95	2610	8	325	1565	1585	11·2	60
66	0·105	0·05	35	0·095	2	1	140	2610	12	217	1565	1585	11·2	60
67	0·06	0·05	30	0·02	1	1	50	3120	10	310	1570	1620	7·4	16
68	0·075	0·05	60	0·025	1*	1	110	4010	14	286	1570	...	10·8	107
69	0·085	0·05	18	0·115	2*	1	105	3110	10	311	1605	...	9·9	55
70	0·085	0·05	42	0·05	2*	1	130	5370	23	233	1540	1562	10·7	31
71	0·10	0·045	51	0·065	2*	1	110	4030	17	237	1572	1604	8·0	53
72	0·06	0·04	48	0·025	2	1	130	12,660	30	420	1540	1580	8·2	25
73	0·12	0·06	51	0·07	2	1	70	5700	25	248	1540	1620	14·5	218
74	0·11	0·05	26	0·14	2	1	65	3390	11	308	1565	1560	8·5	33
75	0·06	0·04	34	0·035	1	1	85	5850	15	390	1565	1560	10·6	19·5
76	0·055	0·04	30	0·03	1*	1	...	3590	13	276	1570	...	13·4	101
77	0·06	0·05	60	0·01	2*	1	170	1840	6	306	...	...	10·6	92
78	0·09	0·04	30	0·10	1	1	90	7770	20	388	1510	1562	11·7	71
													13·4	67

* Two lances used in parallel

Figure 7 shows that there is no appreciable difference in the specific consumption at a high and at a low specific input ; this agrees with the results shown in Fig. 6 where the differences in removal rate are commensurate with the differences in specific oxygen input.

Production of Iron Oxide—The equilibrium between carbon and oxygen in steelmaking reactions is known to be

$$C + FeO \rightleftharpoons Fe + CO.$$

During refining with oxygen there may be a certain amount of direct oxidation according to the reaction

$$2C + O_2 \rightarrow 2CO$$

and to a considerably lesser extent, owing to the high temperatures,

$$C + O_2 \rightarrow CO_2.$$

The normal equilibrium governing the relationship between carbon and oxide of iron will, however, also be valid in oxygen refining practice, and as carbon is oxidized out of the steel so the oxide content of the metal must increase. This will be reflected by an increasing oxide content in the slag since the equilibrium between [FeO] in the metal and (FeO) in the slag is governed by the composition of the slag.

At Brymbo a routine estimation of the iron oxide content (as Fe) of the slag during refining is carried out. Figure 8 shows the general effect of the reduced carbon content on the slag iron when using the oxygen lance. Above 0·20% of C the iron content of the slag does not increase noticeably with the reduction of the carbon, but below this point the production of iron oxide is very pronounced. The position of the curve in Fig. 8 corresponds very closely with that of the derived (dotted) curve in Fig. 5*b*, showing that the failure of the oxygen 'efficiency' at reduced carbon contents may be due largely to the increasing quantities of FeO necessary for the reaction to proceed.

The equilibrium (FeO) slag $\rightleftharpoons$ [FeO] metal in basic steelmaking practice may be forced to the right if the lime/silica ratio of the slag is lowered. A few experiments were carried out at Brymbo in which a little dry sand was added to the slag during the latter stages of the boil. A slight drop in the iron content of the slag and in the carbon content of the metal was noted, but erosion of the banks on the slag line occurred and the experiments were discontinued.

Summary—The curves plotted in Figs. 4, 5, 6, 7, and 8 give an indication of the mechanism of decarburization of a bath of steel (under electric furnace conditions) by means of a blast of oxygen. These may be summarized as follows :

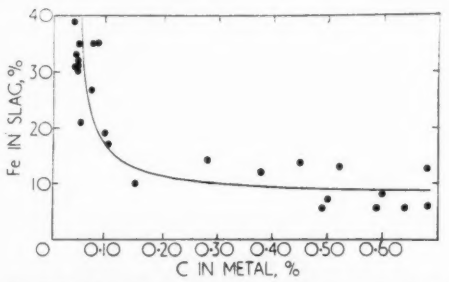


Fig. 8—Relation between bath carbon and slag iron during oxygen injection (18- and 29-ton furnaces)

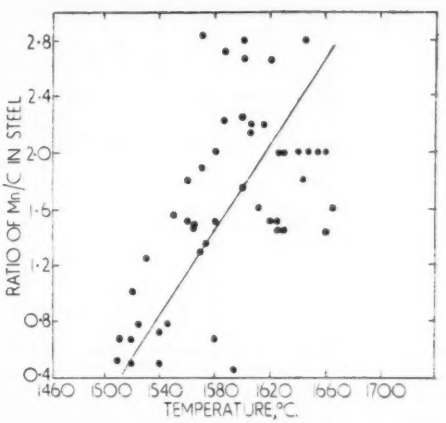


Fig. 9—Relation between temperature and Mn/C ratio (18- and 29-ton furnaces)

The process is governed by three variables : the rate at which the oxygen can be fed to the bath, the rate at which the carbon in the bath is able to react with the oxygen, and the quantity of iron oxide necessary to maintain slag/metal equilibrium. The last two variables are governed almost entirely by the concentration of carbon in the steel.

At a high-carbon concentration the 'activity' of the bath carbon is at its maximum and FeO requirements at a minimum, and the rate of carbon reduction will be the rate at which every molecule of bath carbon can come into contact with a molecule of oxygen or iron oxide. As the carbon content falls, however, so does the speed at which carbon can react with oxygen, largely owing to dilution, and below 0·20% of carbon the quantity of oxygen which is used up in the production of unwanted iron oxide rapidly increases. Therefore, if the blowing continues at a steady rate there will be a rapid drop in the apparent efficiency of oxygen usage.

In the two furnaces at Brymbo the specific consumptions at high-carbon contents and low-carbon contents are very much the same in each case (*see* Figs. 5 and 7). Differences occur in the intermediate ranges, between 0·30% and 0·10% ; in the 18-ton furnace the reaction rate falls before the effect of the iron oxide produced is felt, but in the 29-ton furnace this does not occur.

Oxygen Balance

Five of the 29-ton heats have been assessed for an oxygen balance by weighing the slag after blowing. The results are shown in Table V. The production of oxide of iron, expressed as FeO, accounts for approximately the same percentage of the oxygen as the production of CO. About 30% of the oxygen blown is unaccounted for ; this may represent either the production of higher oxides of iron (Fe_2O_3) or the production of a certain amount of CO_2—probably both.

In general, these oxygen balances agree with the results for the specific consumption of oxygen.

Table V

29-TON HEATS : OXYGEN BALANCE

Cast No.	Initial Carbon Content, %	Final Carbon Content, %	Carbon Removed, lb.	Oxygen to form CO, lb.	Manganese Removed, lb.	Oxygen to form MnO, lb.	Phosphorus Removed, lb.	Oxygen to form P_2O_5, lb.	Slag Weight, lb.	Increase in Fe Content, %	Oxygen to form FeO, lb.	Oxygen Blown, lb.	Oxygen to Remove Carbon, %	Oxygen to Remove Manganese, %	Oxygen to Remove Phosphorus, lb.	Oxygen to form FeO, %	Oxygen Unaccounted for, %
S1	0·40	0·05	203	271	150	44	23	30	5700	11·0	179	917	29	5	3	19	44
S2	0·43	0·045	223	296	110	32	17	22	3900	28·0	312	925	32	3	2	34	29
S3	0·70	0·04	382	510	232	67	23	30	6700	17·0	326	1175	43	6	3	28	20
S4	0·34	0·05	168	224	128	37	24	31	6150	13·0	228	645	34	6	5	35	20
S5	0·30	0·045	148	198	122	35	6	8	7000	18·0	358	866	23	4	4	41	28

Reduction of Manganese with Oxygen

The oxidation of manganese during oxygen injection is not appreciably greater than in a normal ore boil. In the presence of carbon the oxidation is largely governed by the effect of temperature on the equilibrium $MnO + C \rightleftharpoons Mn + CO$. Increased temperature forces this equilibrium to the right as in the case of the equilibrium between carbon and chromium,[6] and the stable Mn/C ratio increases (Fig. 9). Pumping in oxygen therefore frequently fails to increase the rate of removal of the residual manganese. At a very high temperature this is even more marked (*see* p. 409).

The considerable scatter in these results is probably due to the loss, by intermediate de-slagging, of some of the manganese that might otherwise be recovered from the slag at higher temperatures.

Lance Life and Oxygen Pressure

The life of a lance is determined by the volume of gas which can be passed through it before it becomes so short that further working is impossible. The rate at which a lance is used up depends upon a number of factors such as gas flow, gas pressure, bath temperature, etc., and on the slag volume and the skill with which the operators 'slag' the lance and hold it in the furnace during the blow. The carbon content of the bath may also be an important factor. When blowing down from a high carbon, a lance may last a considerable time, probably owing to the protective action of the frothing slag which actually 'chills' on the lance during blowing. It is impossible to predict the life of any lance under given circumstances, but Fig. 10 gives the general results obtained

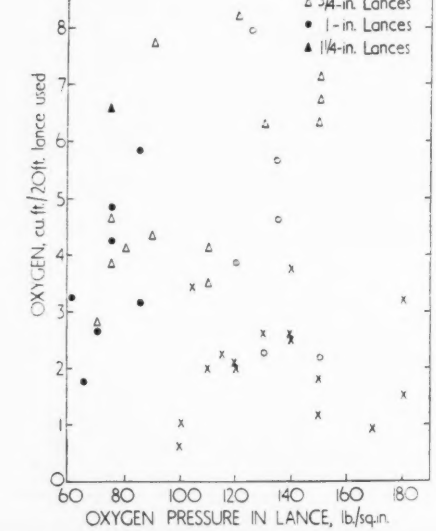


Fig. 10—Relation between lance life and oxygen pressure

for different lances at Brymbo and gives the various pressures in the lance.

The results show that the pipe size most suitable for lancing is $\frac{3}{4}$-in. steam pipe ; a 20-ft. length of $\frac{3}{4}$-in. pipe enabled as much as 9000–10,000 cu. ft. of oxygen to be pumped into the bath at one blow, at an optimum lance pressure of about 100–120 lb./sq. in. Generally, increased pressure improved lance life. The poorest life was obtained from $\frac{3}{8}$-in. pipes, which are not entirely suitable at the maximum pressure of 180 lb./sq. in. With a $\frac{3}{8}$-in. lance (or two $\frac{3}{8}$-in. lances in parallel) the best life was obtained at 130–140 lb./sq. in.

The results show that the life of a $\frac{1}{2}$-in. lance is intermediate between that of a $\frac{3}{8}$-in. and $\frac{3}{4}$-in. lance ; there is insufficient evidence available to say whether or not it lasts longer at a high working pressure. With a 1-in. pipe it is not possible to raise the lance pressure (at the present rate of oxygen evaporation) to much above 80 lb./sq. in. Lance life under these conditions seemed to be reasonably good, and to improve with increasing pressure. The one test with a $1\frac{1}{4}$-in. pipe was fairly good at low pressure, but conclusions cannot be justifiably drawn from this.

Temperature Rise during Blowing

Bath temperatures were measured with a Tinsley Recording Immersion Pyrometer.

It was found that during injection with the oxygen lance the bath temperature may be substantially increased, and on occasions, in the 18-ton furnace, quantities of cold scrap were fed by hand during the boil to keep the temperature down to avoid increased erosion of the hearth. The heat generated during this period is entirely due to the exothermic reactions with the oxygen, since the electrodes are raised and the current switched off.

Figures 11 and 12 illustrate the general trend of the temperature increments at varying degrees of carbon reduction, different carbon ranges, and different specific oxygen inputs. In general a high rate of oxygen input tends to give a higher temperature increment. In the lower carbon ranges, even although the oxygen input may be quite low, the increment is greater. This indicates that the rise in temperature is due primarily to the heats of formation of oxides of iron, which are very much higher than the heat of combustion of carbon. In the lower carbon ranges, where the production of iron oxide is considerable, a rise in temperature of about 30° C. is possible for a fall of only about four points of carbon. Blowing oxygen into high-carbon baths, where the bulk of the oxygen is consumed by the carbon, will give a rise of about 100° C. for the loss of 80 points of carbon in the 18-ton furnace, and about 80° C. for 50 points of carbon, in the 29-ton bath. Thus the temperature rise per point of carbon removed is about seven times greater in the low carbon ranges ; this is to be expected since the oxygen input per point of carbon removed is 3–13 times greater under these conditions. An unusually rapid temperature rise in the high carbon ranges is probably due to a high silicon content in the bath.

The two heats in which 6 cwt. of scrap were added are shown (dotted) in Fig. 11*a* ; one appears to be unaffected by the scrap addition, whereas the other shows a slight flattening off.

The results given in Figs. 11 and 12 indicate that if the specific oxygen input were lowered to about 5–8 cu. ft./ton/min. there would probably be no temperature increment during injection, and there might even be a marked temperature drop. This is a further indication of the importance of a sufficiently high oxygen input rate for work of this nature.

Examination of Tables I–III shows no correlation between temperature and either the rate of carbon elimination or the specific oxygen consumption. Equally good rates of elimination and oxygen consumption were obtained for both high and low initial temperatures. Theoretically, a high temperature would tend to enhance the elimination of carbon and suppress the oxidation of iron, but within these ranges of carbon and temperature this effect could not be detected, or it was masked by the other variables.

Power Savings with Oxygen Injection

During oxygen lancing at Brymbo the power input to the furnace is reduced to zero, and Fig. 13 illustrates the magnitude of the power economies obtained with oxygen refining in the 29-ton furnace ; these increase

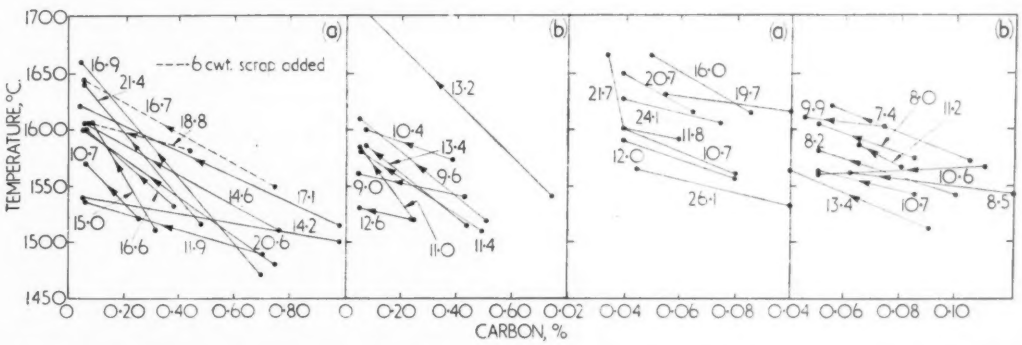


Fig. 11—Temperature increment during oxygen injection (high C) : (*a*) 18-ton furnace, (*b*) 29-ton furnace. Figures on curves are specific oxygen inputs

Fig. 12—Temperature increment during oxygen injection (low C) : (*a*) 18-ton furnace, (*b*) 29-ton furnace. Figures on curves are specific oxygen inputs

with rise in melt-out carbon. When oxygen is used the power consumed between clear-melt and end of boil varies between 500 and 3000 kWh., and is only very faintly, if at all, correlated with melt-out carbon. During this period power input to the furnace is used mainly to flux lime or limestone additions to the slag. When iron ore is used for boiling, the furnace consumes power throughout the longer oxidizing period, and the power used between clear-melt and slag-off varies from 4000 to 10,000 kWh., consumption rising at the rate of about 1000 kWh. for every 10 points of carbon removed.

The relative economies of the two refining techniques in the 29-ton furnace may be estimated as follows :

	Iron ore		Oxygen	
Carbon at melt-out, %	0·30	0·60	0·30	0·60
Time, hr.	1½–2	3	¾	1½
Power, kWh.	5000	8000	2000	2400
Oxygen, cu. ft.	none	none	7000	13,000

Excluding the saving in iron ore, which may be considerable, and the variable cost of pipe consumption, for boiling down a 0·30% C heat, the expenditure on 7000 cu. ft. of oxygen is offset by a time-saving of about 1 hr. and a saving of 3000 kWh. of power. For a 0·60% C heat 13,000 cu. ft. of oxygen is balanced by 1½ hr. and 5600 kWh. With power at ¾*d.*/unit, even with oxygen costing 15*s.*–17*s.* 6*d.*/1000 cu. ft., oxygen refining is less expensive, although a slight reduction in overall yield occurs, due to the absence of the iron ore addition and consequent increase in total bath weight.

CONCLUSIONS

The general features of the results obtained using the oxygen lance at Brymbo may be summarized as follows :

(1) To improve the rate of carbon removal to anything over the normal rate of 0·20%/hr., the oxygen flow must be above the rate of 5 cu. ft./min./ton of steel in the bath.

(2) At high carbon ranges the rate of carbon elimination may be very rapid and directly commensurate with the rate of oxygen input.

(3) As the bath carbon falls so the rate of reaction between carbon and oxygen falls and the quantity of FeO necessary to maintain equilibrium in the bath increases ; the rate of carbon elimination falls and the oxygen used per degree of carbon elimination rises.

(4) At high carbon ranges roughly 7·5 cu. ft. of oxygen are needed per 0·01% of C removed per ton of steel. This is maintained until either the rate of reaction between carbon and oxygen lags behind the rate of oxygen feed and/or the quantity of FeO required for equilibrium conditions rises sharply, when a drop in the specific oxygen consumption (cu. ft./pt. of C/ton) occurs. The carbon content at which this failure of efficiency occurs varies according to the rate of oxygen input. With a specific oxygen input of

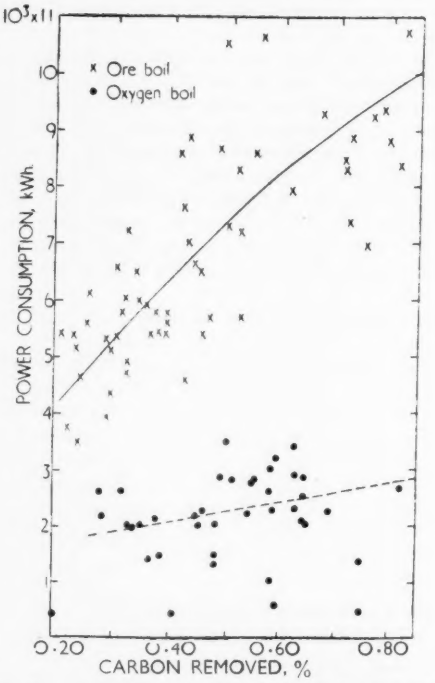


Fig. 13—Power consumption during refining in a 29-ton furnace

between 10 and 20 cu. ft./ton/min. failure takes place at about 0·40% of C ; at 8–13 cu. ft./ton/min. the specific consumption of 7·5 cu. ft./pt. of C/ton is maintained down to 0·20% of C.

(5) At oxygen input rates above 5 cu. ft./ton/min. the bath may be sensibly heated during injection since the sum of the chemical reactions removing the carbon are exothermic ; with iron ore they are endothermic. The lower the bath carbon, the greater is this effect, due to the quantity of iron oxide formed.

(6) No correlation exists between bath temperatures and specific oxygen consumption at least in the ranges 0·80–$<$0·10% of C and 1500–1700° C.

(7) ¾-in. steam pipe appears best for lancing. In general, increased pressure makes for longer lance life except in the case of ⅜-in. pipes.

(8) Since the bath is heated during injection no current is used. When boiling down from a relatively high carbon content at melt-out, economic considerations of oxygen consumption against time and power saved, show a balance in favour of oxygen.

Acknowledgments

The authors wish to thank the Directors of Messrs. Brymbo Steelworks Ltd., for permission to publish this paper, and, in particular, Mr. Morse for his help and encouragement.

Part II—THE USE OF THE OXYGEN LANCE IN STAINLESS STEEL PRODUCTION

By W. H. Everard and D. J. O. Brandt, A.R.S.M., B.Sc., A.I.M.

SYNOPSIS

The technique of blowing oxygen into the bath of a 4-ton Heroult furnace through a ¾-in. wrought iron tube during the refining period is described and details of carbon reduction and chromium loss are given.

The physical chemistry of this process is briefly reviewed and data are set out showing the alteration of composition and temperature during oxygen injection. It is shown that a high initial silicon content of the metal may protect the chromium against oxidation, but may hinder subsequent re-chromizing with ferro-silicon.

The log sheet of a typical heat is included.

Introduction

THE use of the oxygen lance was adopted experimentally towards the end of 1947 by Messrs. Edgar Allen and Co., Ltd., Imperial Steelworks, Sheffield. Encouraging results were obtained in the production of stainless steel in a 4-ton Heroult furnace from 100% stainless scrap charges, and by September, 1948, a technique had been evolved which enabled the process to be used on a production basis. Since that time, the production of stainless steel from 100% stainless scrap charges using the oxygen lance has been a matter of regular routine, and the results obtained are given in this paper.

The use of the oxygen lance raises a number of new features regarding the behaviour of alloy steel baths at high temperatures, much of which is not yet fully understood. It is hoped to publish further data as both knowledge and technique improve.

The Value of Oxygen Refining in Stainless Steel Production

The use of the oxygen lance for refining a high-chromium steel, as opposed to its use in non-chrome steels, enables the heat to be worked at a temperature some 200° C. higher than normal, as explained in the Foreword. Oxygen rapidly attacks the oxidizable elements, and the very high heat of formation of SiO_2 and Cr_2O_3 (or CrO) can raise the bath temperature to well over 1800° C. (estimated) in a few minutes. Feeding the bath with iron oxide does not give the same results ; the reactions are much slower, since the oxide (ore or scale) must be first melted and absorbed into the bath.

The higher the bath temperature the less stable are the oxides of chromium, manganese, iron, and silicon, and the more stable is the oxide of carbon, CO. In an oxidized bath the formation of carbon monoxide will therefore be enhanced and the formation of the metallic oxides repressed, so that the carbon may be removed with a reduction in the losses of chromium (and manganese) which are normally unavoidable in ore-refining practice. Owing to the losses of chromium into the slag, making it extremely thick and heavy at normal steelmaking temperatures, it is virtually impossible to refine a 100% stainless scrap charge with an ore boil. With oxygen, and with the extra 200° C. bath temperature available, this is now an everyday practice.

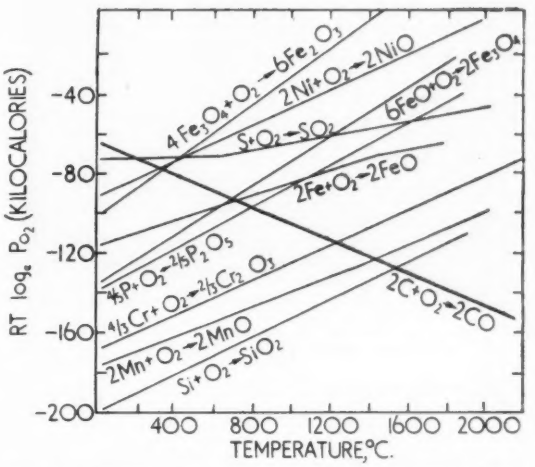


Fig. 14—Stability of various oxides with temperature (Ellingham[7] and Richardson and Jeffes[8])

Graphs of ' free energy ' of formation plotted against temperature of various oxides have been given by Ellingham[7] and revised and extended by Richardson and Jeffes.[8] The relevant portions of these curves are shown in Fig. 14. The lower the point on any curve, the more stable is the oxide in question ; thus, as the temperature rises the rate of oxidation of carbon in the bath increases and the rate of oxidation of the other elements is slower. In other words, the higher the temperature the greater will be the stable Cr/C ratio in the steel, and low-carbon contents should be obtained without a high chromium loss. In practice, difficulty is experienced in removing the carbon below 0·08% (in the presence of chromium) even though the bath temperature is high. The lower the carbon content the greater is its reluctance to oxidize at any given temperature, whereas oxidation of the chromium continues.

Paper SM/AC/21/50 of the Electric Process Sub-Committee of the Steelmaking Division of the British Iron and Steel Research Association, received 27th March, 1950. The views expressed are the authors' and are not necessarily endorsed by the Sub-Committee as a body.

Mr. Everard is on the staff of Messrs. Edgar Allen and Co., Ltd.

Fig. 15—4-ton Heroult furnace used for the production of 65-cwt. stainless heats with oxygen

When ore or scale is fed into a furnace in which there is a slag containing oxides of chromium, some of it may be 'passivated' owing to attack by Cr_2O_3 forming a hard refractory layer of the double oxide, $FeO.Cr_2O_3$, on its surface, thus hindering the attack on the carbon in the bath.[3] With oxygen this does not occur.

The chromium-bearing slag obtained in the oxygen-refining of stainless steel can be reduced by ferro-silicon, and an appreciable portion of chromium oxidized during blowing may be recovered and returned to the metal. Thus, the addition of virgin chromium in the form of low-carbon ferro-chromium is cut down to a minimum.

Practical experience has shown that all these features, together with the fact that during oxygen refining the electrodes in the arc furnace may be raised and the current cut off, mean that the economies gained will amply offset the expenditure necessary for the oxygen. The production of stainless steel by this process is rapidly becoming a standard practice on both sides of the Atlantic.

STEELMAKING PRACTICE AT MESSRS. EDGAR ALLEN AND CO., LTD.

Details of Operation

A 4-ton Heroult-type tilting electric arc furnace, with a transformer of 750-kVA. capacity is in use at Messrs. Edgar Allen and Co., for the oxygen refining of stainless steel (Fig. 15). Electrode pillars are located opposite the taphole, and the furnace is worked through two side doors opposite each other. At present, this furnace is equipped with a monolithic dolomite hearth and side walls, and a silica roof.

The Lance—The oxygen lance consists of naked 20-ft. lengths of standard $\frac{3}{4}$-in. wrought iron tube and is introduced through the taphole. The lance end is held just below the metal surface and is moved slowly forward during the blow as the pipe is consumed. Oxygen is fed to the lance through $\frac{3}{4}$-in. dia. rubber hose.

Oxygen Supply—Pending the supply and erection of a liquid oxygen evaporator and storage-tank arrangement, oxygen is supplied to the furnace from two 2000-cu. ft. capacity cylinders at 150 atmos.* From the cylinder cock the gas passes through hard-drawn

SCHEDULE

Oxidation of Carbon by Molecular Oxygen in 18 8 Heats using 100% Scrap

Heat A6, October, 1949
Charged 69 cwt. MYAWP (18% Cr, 8% Ni, 0·35% Ti) scrap
10.40 a.m. Power on
12.40 p.m. Melted, and No. 1 steel and slag samples taken (reducing slag)
Analysis of steel : 0·17% C, 0·32% Si, 0·029% S, 0·020% P, 0·60% Mn, 18·48% Cr, 8·22% Ni, 0·10% Ti
1.40 p.m. Temperature, 1600° C.
1.43 p.m. Slagged off
1.45 p.m. Commenced first blow
Blew continuously for 3 min. 15 sec.
Pressure 150 lb./sq. in.
Flow 570 cu. ft./min.
Volume used 1850 cu. ft.
Pipe used 14 ft. $\frac{3}{4}$-in. W.I. tube
1.50 p.m. No. 2 steel and slag samples taken
Analysis of steel : 0·14% C, 0·04% Si, 0·028% S, 0·029% P, 0·36% Mn, 16·48% Cr, 8·55% Ni, 0·02% Ti
1.55 p.m. Commenced second blow
Blew in 4 periods, 1 min. 27 sec. ; 1 min. 22 sec. 1 min. 30 sec. ; 1 min. 30 sec.
Pressure 150 lb./sq. in.
Flow 322 cu. ft./min.
Volume used 1850 cu. ft.
Pipe used 14 ft. $\frac{3}{4}$-in. W.I. tube
2.5 p.m. No. 3 steel and slag samples taken
Analysis of steel : 0·05% C, 0·002% Si, 0·032% S, 0·032% P, 0·26% Mn, 12·02% Cr, 8·22% Ni, 0·00% Ti
2.10 p.m. 3 cwt. MYAWP plate scrap 60 lb. of Ni } Added
65 lb. ferro-silicon 75% Si (lump) } to
100 lb. ferro-silicon 75% Si (powder) } bath
2.25 p.m. No. 4 steel and slag samples taken
Analysis of steel : 0·07% C, 0·25% Si, 0·044% S, 0·031% P, 0·42% Mn, 14·48% Cr, 8·22% Ni, 0·02% Ti
2.40 p.m. Reducing slag removed
2.45 p.m. 500 lb. ferro-chrome (0·06% C, 70% Cr) added to bath
2.55 p.m. Temperature, 1540° C.
2.56 p.m. Electrodes lowered
3.20 p.m. Temperature, 1600° C.
3.30 p.m. Tapped, and 130 lb. of $\frac{1}{2}$% ferro-titanium (40% Ti) added to stream entering ladle
Analysis of steel : 0·07% C, 0·30% Si, 0·029% S, 0·030% P, 0·46% Mn, 17·34% Cr, 7·90% Ni, 0·38% Ti
Finished

Charged	76½ cwt. (69 cwt. of scrap ; 7½ cwt. of alloys and plate scrap)
Tapped	70 cwt.
Loss	6½ cwt.
Yield	91·5%
Loss	8·5%
Duration of heat	5 hr. 20 min.
Power used	2300 kWh.

* Since this paper was written this arrangement has been replaced by a liquid oxygen evaporation system.

copper tubing and the pressure is reduced to 150 lb./sq. in. (about 10 atmos.) by means of a reducing valve, before entering the rubber hose and the lance. Pressure gauges are fitted to the inlet and outlet of the reducing valve, and from the fall in the inlet pressure the volume of gas taken from the cylinder at any time can be readily computed. The two gas cylinders necessary for one heat are used consecutively, not in parallel (*see* Fig. 16).

Progress of a Heat—A copy of the log sheet of a typical heat of stainless steel made with oxygen from a 100% stainless scrap charge is given in the Schedule (p. 412). Average practice for some 16 consecutive heats made in the period June–October, 1949, is as follows :

The furnace is hand-charged with roughly 67 cwt. of metal and 140 lb. of limestone. The melting slag is kept in a reducing condition to minimize chromium loss at this stage; hence a carbon pick-up takes place. Melting is complete in about 3 hr., when the electrodes are raised and the heat is slagged. Bath temperature is now about 1580–1620° C., and directly the metal is clear the oxygen blowing commences.

Blowing takes place in two separate stages, because of the need to change the cylinders half way through the operation. The bath is sampled at the change-over and at the end of the second blow. During blowing an estimated temperature of approx. 1800–1900° C. is reached and a very considerable volume of slag collects during the blowing period because of the unavoidable attack on the furnace banks and bottom at this high temperature.

When blowing is complete, if the slag is fluid enough with excessive 'topheat,' about 3 cwt. of cold stainless plate scrap is added to the bath to reduce the temperature and the bath is fed with about 180 lb. of 75% ferro-silicon, in the proportions of four parts lump and five parts crushed. This is stirred gradually into the slag to reduce chromium oxide ; when reduction is complete the furnace is again sampled and slagged. The series of operations—blowing, sampling, blowing again, sampling, reducing, sampling, and slagging, takes about one hour for completion.

A new slag is then made and the final addition of alloys added. If necessary the electrodes are lowered to bring the heat to a tapping temperature. The total heat time averages 5½ hr., the power consumption about 625 kWh./ton, and the oxygen consumption 1080 cu. ft./ton.

The chemical composition of the metal at the various stages may vary considerably. The chemistry of oxygen blowing and subsequent reduction from the slag is dealt with in greater detail on p. 415, average figures for the analysis of the metal, however, are as follows :

	C, %	Si, %	S, %	P, %	Mn, %	Cr, %	Ni, %
Before blowing	0·18	0·44	0·017	0·021	0·69	18·24	8·20
After first blow (1962 cu. ft. of O_2)	0·14	0·10	0·021	0·027	0·47	16·56	8·36
After second blow (1852 cu. ft. of O_2)	0·07	0·030	0·029	0·031	0·33	14·39	8·53
After reduction with ferro-silicon	0·076	0·33	0·033	0·031	0·51	15·17	8·59
Final composition	0·081	0·47	0·022	0·029	0·57	17·76	8·20

Fig. 16—Oxygen storage and control system showing cylinders, reducing valve pressure gauges, etc.

Generally, about 1·5–3% of chromium is lost in the first blow, and a further 2% in the second blow. Of this loss some 1% can be made up by the reduction with ferro-silicon, leaving between 2 and 3% to be supplied from the ferro-chrome. Losses during melting and refining average 5 cwt., *i.e.*, 7·5%. On the average, 2·6% of Cr, in the form of ferro-chrome, and 0·60% of Ni, are added.

Technique of Blowing

During the initial experimental stages it was found that the removal of carbon and the life of the lance were improved the higher the rate of flow of oxygen into the bath. Gas is now fed to the bath at a rate of 438 cu ft./min., and at an initial pressure of 150 lb./sq. in. which is not allowed to fall below 120 lb./sq. in. The operation requires control to prevent a violent reaction which may damage the furnace refractories.

At the commencement of blowing the lance is inserted through the taphole and an observer is stationed at one of the side doors of the furnace. The oxygen is then turned on and the lance end pushed just below the metal surface at about 30° to the horizontal (*see* Fig. 17). If the bath shows a tendency to rise dangerously, blowing ceases for a few minutes to allow the bath to subside. Blowing finally ceases when the inlet pressure falls below 120 lb./sq. in., or in the case of the second blow, when the bath goes dead. The behaviour of the bath appears quite arbitrary; sometimes it is possible to make a continuous blow using the first 2000 cu. ft. and at other times it may be necessary to adopt the above intermittent practice.

Two types of slag are obtained by varying the method of introduction of the lance. If kept in the steel there is a more rapid erosion of the lance and a bulky and dense slag is formed ; on the other hand if the lance end is in the slag the latter becomes more

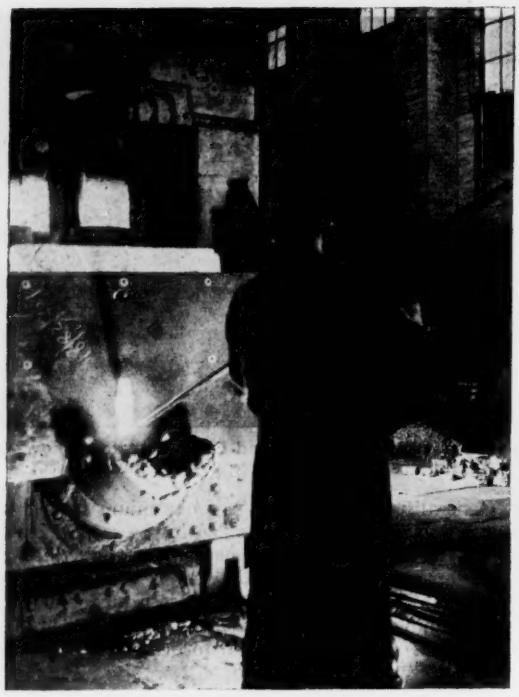


Fig. 17—Commencement of oxygen blowing with observer stationed at side door of furnace

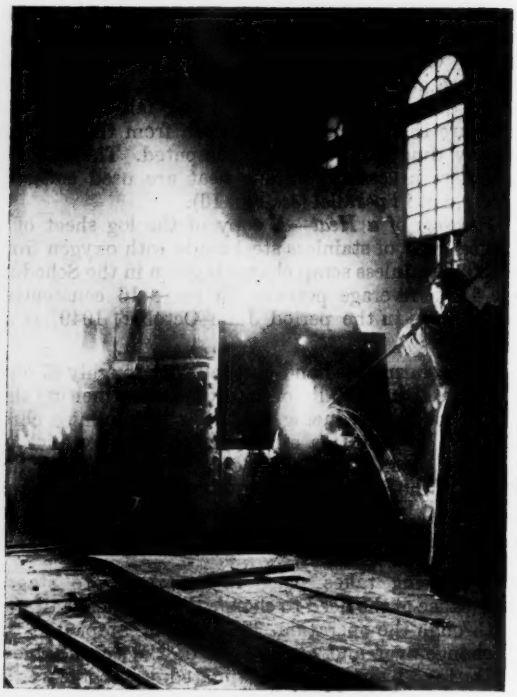


Fig. 18—Oxygen lancing in progress on a 4-ton Heroult furnace showing fumes and flames

fluid and 'watery.' The former method is more satisfactory because the thick slag 'blankets' the heat from the top refractories, and the addition of scrap is not needed to cool the slag. The reason for this variation in the slags is not yet properly understood.

Pipe consumption averages 17 ft. for the first blow and 15 ft. for the second blow, *i.e.*, 0·90 ft./100 cu. ft. and 0·83 ft./100 cu. ft. respectively. A distinct correlation between lance life and rate of gas flow is shown in Tables VII and VIII. This is probably due to the improvement in the cooling action with the faster gas flows.

Oxygen blowing is characterized by the formation of fume and by the appearance of flames at the various exits in the furnace structure, *i.e.*, doors, electrode holes, etc. (*see* Fig. 18). During the first few minutes fume is predominant ; as the reaction gets under way, it is replaced by a large, hot, bright, yellow flame.

Summarizing, the practical aspects of the process present no particular difficulties apart from the, at present, unavoidable wear on the dolomite hearth at the high temperatures involved ; oxygen should be fed into the bath at a rate as fast as is consistent with safety, and at a pressure of not lower than 120 lb./sq. in. Lance life and chemical efficiency are improved by a faster rate of oxygen flow.

A chromium recovery of 83% on all scrap charge

Table VI

COMPARATIVE CARBON AND CHROMIUM ANALYSIS

Heat No.	Carbon Analysis			Chromium Analysis			
	Initial Carbon in Bath, %	Carbon After Reducing, %	Carbon Oxidized, %	Initial Chromium in Bath, %	Chromium Content After Reducing, %	Chromium Not Reduced, %	Chromium Recovery on Initial Cr, %
A 1	0·18	0·09	0·09	17·49	14·15	3·34	80·9
A 2	0·16	0·12	0·04	17·23	14·84	2·39	86·7
A 3	0·20	0·06	0·14	19·14	16·09	3·05	84·1
A 4	0·12	0·08	0·04	17·97	14·82	3·14	82·6
A 5	0·16	0·10	0·06	17·80	15·23	2·57	85·6
A 6	0·17	0·07	0·10	18·48	14·48	4·00	78·4
A 7	0·14	0·07	0·07	18·88	15·72	3·16	83·3
A 8	0·19	0·05	0·14	18·80	15·68	3·12	83·4
A 9	0·26	0·07	0·19	18·94	16·15	2·79	85·3
A10	0·19	0·05	0·14	17·68	14·52	3·16	82·2

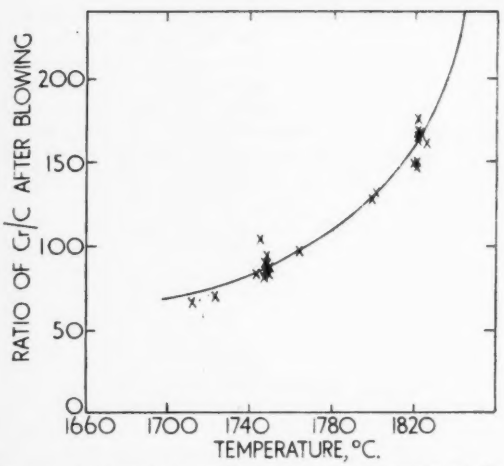


Fig. 19—Cr/C ratio in oxidized chrome steel melts (after Hilty[6])

is obtained; the oxygen consumption averages 1080 cu. ft./ton tapped, power consumption 630 kWh./ton. Overall recovery is 93%.

Typical results showing the carbon removed, the chromium lost, and the chromium recovered are given in Table VI.

CHEMISTRY OF REFINING STAINLESS STEEL WITH OXYGEN

Discussion of Results

Three tables have been drawn up giving details for ten recent heats at Edgar Allen and Co., Ltd. These tables record the changes in composition, etc., for the first blow, the second blow, and the reduction by ferro-silicon, and in each case an attempt has been made to calculate the ' efficiency ' of the reaction and to estimate the approximate temperature at which it took place.

One of the principal difficulties which at present stand in the way of a clearer appreciation of the chemical mechanism of this process is the fact that the temperatures involved are necessarily very high. Owing to the high heats of combustion, the oxidation of chromium and, in particular, of silicon, forces the bath temperature into ranges which cannot be measured with the normal type of Pt/Pt–Rh immersion pyrometer. An understanding of the chemical mechanism of the refining process is thereby hindered.

The work of Hilty[6] in the U.S.A. has demonstrated that in a bath of chromium-bearing steel under the action of the oxygen lance in the laboratory there is a well-marked relationship between the chromium/carbon ratio in the bath and the bath temperatures. The results recorded in Hilty's laboratory experiments (Fig. 19) show a logarithmic relationship between Cr/C and temperature. If it is assumed that conditions in the electric arc furnace under the action of the oxygen lance are reasonably similar to conditions in Hilty's laboratory-scale experiments, then an estimate of the bath temperature during oxygen injection on Edgar Allen's 4-ton furnace may be made from the Cr/C ratio of the steel, extrapolating where necessary.

This device has been resorted to in all cases where the bath temperature is higher than an immersion thermocouple can record, and the results are included in Tables VII, VIII, and IX. It must be stressed, however, that these temperatures are only estimates, and liable to error, especially when extrapolation was necessary.

It is generally assumed that the stable oxide of chromium is the chromic oxide, Cr_2O_3, and that this compound exists in the bath under oxidizing conditions. Hilty, however, has suggested the existence of the lower oxide CrO, in the steel, which may be wholly or partly converted to Cr_2O_3 in the slag. Further evidence on this point has been submitted by Chen and Chipman,[9] Clark,[10] and Körber and Oelsen.[11] The latter state that in acid slags the lower oxide CrO definitely preponderates.

At the start of oxygen injection at Edgar Allen and Co., Ltd., the metal is free of slag; this builds up during the oxidation due to erosion of the bottom and banks of the furnace. It may thus vary in both bulk and composition within wide limits, and under present conditions it is impossible to state whether at any time it is more acid than basic or *vice versa*. Slag samples are not drawn during refining, and as they are difficult to dissolve their analysis is not straightforward.

The figures for reaction efficiency given in Tables VII, VIII, and IX have been calculated on the assumption that all the chromium is oxidized to Cr_2O_3 in the slag. This does not deny the possible existence of CrO in the metal, but in any case the actual quantity of chromium existent in this form would be extremely small. Oxygen equivalents and silicon equivalents are calculated on the basis of the equations:

$$4Cr + 3O_2 = 2Cr_2O_3, \text{ and } 2Cr_2O_3 + 3Si = 4Cr + 3SiO_2$$

Results of First Blow

The following facts emerge from an examination of the results given in Table VII:

Efficiency—Between 50% and 70% of the oxygen blown oxidizes alloying elements. High initial silicon and carbon contents tend to give the best efficiency figures (*see* heats A3 and A5).

Effect of Silicon—A high initial silicon content (due to silicon in the scrap charged), exerts a protective action on the carbon, chromium, and manganese. The affinity of silicon for oxygen at these temperatures is roughly the same as that of carbon, and markedly greater than that of manganese (Fig. 14), and therefore provided that these constituents are present in sufficient concentrations to be equally active, the silicon will tend to be oxidized first. The final columns in Table VII indicate that, in many cases, the bulk of the oxygen used in the first blow is consumed by the oxidation of the silicon.

Temperature Increment—The temperature rise during blowing, as estimated by the Hilty formula, appears to be very largely dependent on the silicon and chromium oxidized, which is to be expected, as these two oxides have the highest heats of formation.

Oxidation of Manganese—Manganese is also protected by silicon (*see* Fig. 14), and, consequently, although the initial manganese content may be

Table VII

DETAILS OF ANALYSIS FOR FIRST OXYGEN INJECTION

Heat No.	Scrap Charge Weight, cwt.	Starting Temp., °C.	Oxygen Blown		Length of ¼-in. W.I. Tube Consumed, ft.	Analysis of Steel before (B) and after (A) Blowing, %														Cr/C After Blowing	Temp. After Blowing, °C. (Hilty)	Approx. Temp. Rise, °C.	Oxygen Equivalents Removed, lb.			Efficiency %
			Vol., cu. ft.	Rate, cu. ft./min.		C		Si		S		P		Mn		Cr		Ni					C	Si	Mn	Cr	
						B	A	B	A	B	A	B	A	B	A	B	A	B	A							
A 1	63	..	2200	366	18	0·18	0·11	0·49	0·001	0·020	0·027	0·027	0·035	0·70	0·37	17·49	14·88	8·73	9·08	135	1806	..	6·6	40	6·7	85	67·5
A 2	63	..	2080	520	14	0·16	0·17	0·77	0·35	0·018	0·027	0·020	0·020	0·61	0·40	17·23	16·37	6·86	6·56	96	1764	..	0·9	34	4·3	28	40
A 3	63	1610	1924	385	17	0·20	0·12	0·80	0·001	0·018	0·030	0·023	0·028	0·57	0·38	19·14	17·37	8·10	7·49	145	1815	205	7·5	65	3·9	57	74
A 4	63	1595	2010	365	14	0·12	0·07	0·34	0·001	0·013	0·020	0·019	0·018	0·68	0·31	17·96	15·80	8·10	8·42	226	1841	246	4·7	27	7·6	70	58·5
A 5	70	1570	1900	519	13	0·16	0·18	1·44	0·48	0·011	0·021	0·026	0·034	0·91	0·84	17·80	16·80	8·80	8·88	93	1758	188	0	86	1·6	36	70
A 6	66	1600	1850	570	15	0·17	0·14	0·32	0·04	0·029	0·028	0·020	0·029	0·60	0·56	18·48	16·48	8·22	8·55	118	1790	190	3·0	24	0·9	68	56
A 7	70	1600	1930	406	32	0·14	0·14	0·40	nil	0·012	0·013	0·020	0·037	0·66	0·37	18·88	16·60	8·44	8·64	118	1790	190	0	37	6·6	83	70
A 8	70	1610	1940	407	22	0·19	0·17	0·51	0·04	0·014	0·022	0·022	0·029	0·58	0·30	18·80	16·90	8·52	8·64	99	1770	160	2·1	42	6·4	69	60
A 9	65	1620	1830	560	16	0·26	0·15	0·39	0·025	0·021	0·029	0·018	0·023	0·89	0·80	18·94	17·16	8·00	8·14	114	1785	165	10·7	30	1·9	59	60
A10	73	1600	1740	512	15	0·19	0·16	0·28	0·060	0·015	0·017	0·020	0·023	0·72	0·41	17·68	16·26	8·24	8·24	101	1771	171	3·3	22	7·4	54	53

noticeably high, the removal of manganese may be relatively insignificant. The rapidly increasing temperature and the considerable quantity of carbon left in the steel also inhibit the oxidation of manganese. As for chromium, increasing temperature stabilizes manganese in contradistinction to carbon; thus a high temperature enables a high Mn/C ratio to exist in the bath. This is shown even more clearly in Table VIII.

Oxidation of Iron—The degree to which iron has been oxidized can only be estimated by the specific consumption. It appears that, in general, between a quarter and a half of the total volume of oxygen blown is consumed in the oxidation of iron.

Sulphur, Phosphorus, and Nickel—At steelmaking temperatures, oxides of these elements are less stable than the oxides of iron, silicon, carbon, chromium, and manganese, and are therefore not removed by oxygen. The increases in sulphur and phosphorus during blowing are partly due to the effect of concentration since the weight of the bath decreases, and partly to the absorption of these elements by the furnace lining from previous heats.

Results of Second Blow

In the second blow there are two important changes—increased temperature and reduced silicon content. The most noticeable effects of these are the reduced temperature increments and the increased degree of oxidation of the chromium. There also appears to be a slight general improvement in the efficiency of blowing, which may be due to the higher temperatures attained.

With the removal of silicon the equilibrium is between the oxides of carbon, manganese, and chromium only. The absence of the silicon causes the chromium to be more easily oxidized, in spite of the higher temperature tending to enhance the oxidation of carbon and inhibit the formation of chromium oxides. In the case of manganese, however, the increased temperature has a more marked effect, and the oxidation of manganese in the second blow is actually less than in the first. The general tendency towards the greater retention of manganese in the second blow compared with the faster oxidation of the chromium in the same period is evident in all the heats.

Apart from these points the behaviour of the steels in the second blow is generally similar to that in the first.

Reduction with Ferro-Silicon

The reduction of chromium from the basic slag after blowing is at present extremely difficult to control, since the volume and composition of the slag are variable. Details of ten heats are set out in Table IX, the last three columns being an estimate of the efficiency of reduction, *i.e.*, the percentage of silicon passing directly to the metal unchanged, the percentage used in reduction of chromium and manganese, and finally, the percentage which is oxidized either by the furnace atmosphere or by the reduction of iron oxides.

About 30–50% of the available silicon is used in the reduction of chromium, the reduction of manganese accounting for about another 3%. 20% is unchanged and enters the metal, and maintains equilibrium with the slag which absorbs SiO_2 from the oxidation of the ferro-silicon. About 50% of the silicon added is

oxidized by the furnace atmosphere or by reduction of iron oxide in the slag.

The chemistry of these reactions is as follows :

Reduction of chromium
$$2Cr_2O_3 + 3Si \rightarrow 4Cr + 3SiO_2$$
Reduction of manganese
$$2MnO + Si \rightarrow 2Mn + SiO_2$$
Reduction of iron
$$2FeO + Si \rightarrow 2Fe + SiO_2$$
(and reduction of higher oxides)
' Fixing ' of silica
$$SiO_2 + \text{free } CaO \rightarrow x CaO.ySiO_2$$

The degree of completion of these reactions in the slag–ferro-silicon reduction process will depend on the activities of the various reactants, or, expressed another way, on the concentrations of free oxides present (chromium, manganese, and iron oxides) and the concentration of free CaO in the slag necessary to fix the silica and to avoid an undesirably high silicon content in the steel. The effect of temperature should only be marked in so far as it affects the activities of these oxides, since silicon has a higher affinity for oxygen than has Cr, Mn, or Fe at all temperatures (*see* Fig. 14).

It is clear that high temperatures do, in fact, appear to assist good chromium recoveries (*see* heats *A*1, *A*4, and *A*6). The recorded temperatures are only estimated after the second blow, the real temperatures being probably much lower due to radiation and conduction losses and to the addition of 3 cwt. of scrap when required.

A second factor which appears to influence the efficiency of the reduction process is the quantity of silica already in the slag. Where a heat starts with a high silicon metal, *e.g.*, *A*5 (initial Si, 1·44%), the SiO_2 in the slag depends on the extent of hearth erosion. If the slag after the second blow is already rich in silica it will probably be unable to absorb much more, and the series of reactions causing reduction of the chromium oxide will be checked. Silicon then either enters the bath unchanged or is oxidized atmospherically without corresponding slag reduction. A high initial silicon content may therefore protect the chromium in the oxidation period at the cost of preventing its subsequent recovery during reduction.

The Slag

The following slag compositions cover the progress of heat *A*6 :

	SiO_2, %	Fe, %	Al_2O_3, %	CaO, %
Melting slag* (reducing conditions)	14·82	2·24	17·04	45·09
After first blow	18·93	5·15	7·32	27·72
After second blow	11·74	4·87	6·33	22·38
After ferro-silicon reduction	21·55	7·23	4·30	27·82
	MgO, %	MnO, %	Cr_2O_3, %	TiO_2, %
Melting slag* (reducing conditions)	8·39	0·85	1·01	8·91
After first blow	6·80	3·21	27·19	1·04
After second blow	4·85	3·27	42·71	0·23
After ferro-silicon reduction	10·79	2·47	22·16	0·17

* Discarded before oxygen injection.

Working on the chromium balance, the weights of the last three slags are by calculation, 807, 1635, and 2050 lb., respectively.

The increase in the slag bulk during the reduction

Table VIII

DETAILS OF ANALYSIS FOR SECOND OXYGEN INJECTION

Heat No.	Scrap Charge Weight, cwt.	Starting Temp., °C. (Hilty)	Oxygen Blown, Vol., cu. ft.	Oxygen Blown, Rate, cu. ft./min.	Length of ¼-in. W.I. Tube Consumed, ft.	Analysis of Steel before (B) and after (A) Blowing, % C		Si		S		P		Mn		Cr		Ni		Cr:C After Blowing	Temp. After Blowing (Hilty), °C.	Approx. Temp. Rise, °C.	Oxygen Equivalents Removed, lb. C	Si	Mn	C	Efficiency %
						B	A	B	A	B	A	B	A	B	A	B	A	B	A								
A 1	63	1806	1650	412	10	0·11	0·07	0·001	0·09	0·027	0·032	0·036	0·029	0·37	0·26	14·88	11·68	9·08	9·08	181	1830	24	3·8	0	2·3	104	71·5
A 2	63	1764	2080	420	10	0·17	0·10	0·35	0·04	0·027	0·053	0·020	0·030	0·40	0·40	16·37	13·39	6·36	7·18	134	1805	41	6·6	25	0	97	66
A 3	63	1815	1923	385	17	0·12	0·07	0·001	0·001	0·030	0·034	0·028	0·035	0·38	0·26	17·37	13·76	7·49	7·49	197	1836	21	4·7	0	2·5	117	69
A 4	63	1840	2010	402	14	0·07	0·06	0·001	0·001	0·020	0·027	0·018	0·024	0·31	0·25	15·80	12·07	8·42	8·73	201	1838	− 2	0·9	0	1·2	121	65·5
A 5	70	1738	1850	385	17	0·18	0·09	0·48	0·18	0·021	0·019	0·034	...	0·80	0·72	16·80	14·98	8·80	9·21	167	1825	67	9·4	27	1·8	66	60
A 6	66	1790	1850	322	14	0·14	0·05	0·04	0·022	0·028	0·032	0·029	0·030	0·56	0·25	16·48	12·02	8·55	8·22	240	(1845)*	(55)	8·9	1·5	6·7	84	58·5
A 7	70	1790	1650	580	21	0·14	0·06	nil	nil	0·013	0·015	0·037	0·025	0·37	0·37	16·60	14·46	8·64	8·48	241	(1845)	(55)	8·4	0	0	81	57
A 8	70	1770	1750	460	22	0·17	0·06	0·04	0·012	0·022	0·028	0·029	0·031	0·30	0·22	16·90	14·08	8·64	8·20	234	(1842)	(72)	11·5	2·5	1·8	102	72
A 9	65	1785	1930	460	12	0·15	0·06	0·025	0·029	0·029	0·029	0·023	0·028	0·80	0·39	17·15	14·06	8·40	8·72	234	(1842)	(57)	7·5	0	8·7	104	67
A10	73	1771	1930	333	16	0·16	0·70	0·060	0·009	0·017	0·023	0·023	0·034	0·41	0·24	16·26	13·10	8·24	8·32	167	1833	62	9·8	4·2	4·0	119	76

* Temperatures in brackets are obtained by extrapolation

Table IX—DETAILS OF ANALYSIS FOR REDUCTION WITH 75% FERRO-SILICON

Heat No.	Scrap Charge Weight, cwt.	Temp. After Second Blow, °C. (Hilty)	Scrap Added to Bath, cwt.	Analysis of Steel before (B) after (A) Scrap Added and after Reducing with Fe-Si, %																Wt. of 75% Ferro-silicon Added, lb.	Weight of Silicon, lb.	Silicon Equivalents Recovered, lb.			Silicon Unaffected, %	Silicon Oxidized	
				C		Si		S		P		Mn		Cr		Ni						Si	Mn	Cr		Usefully, %	Wastefully, %
				B	A	B	A	B	A	B	A	B	A	B	A	B	A									
A 1	63	1830	3	0·07	0·09	0·10	0·25	0·032	0·032	0·039	0·040	0·28	0·40	12·00	14·15	9·08	9·34	185	139	10·5	2·2	58·5	7·5	44	49·5
A 2	63	1805	3	0·10	0·12	0·04	0·63	0·053	0·047	0·030	0·032	0·40	0·65	13·70	14·84	7·18	7·49	185	139	41·5	4·5	33	30	27	43
A 3	63	1836	3	0·07	0·06	0·025	0·53	0·034	0·029	0·034	0·029	0·28	0·54	14·00	16·09	7·49	7·49	180	135	36	4·7	60	27	46·5	26·5
A 4	63	1838	3	0·06	0·08	0·025	0·23	0·027	0·035	0·024	0·028	0·28	0·41	12·30	14·82	8·73	8·73	185	139	15	2·3	72	11	53	36
A 5	70	1825	3	0·09	0·10	0·18	0·64	0·019	0·027	..	0·033	0·72	1·11	15·00	15·23	9·21	9·21	185	139	36	7·8	7·3	26	11	63
A 6	66	(1845)*	3	0·05	0·07	0·025	0·25	0·032	0·044	0·030	0·031	0·28	0·42	12·22	14·48	8·22	8·22	165	124	16·6	2·9	68	13	58	29
A 7	70	(1845)	..	0·06	0·07	nil	0·26	0·015	0·016	0·025	0·028	0·37	0·42	14·46	15·72	8·48	8·52	165	124	20·4	1·0	40	16	33	51
A 8	70	(1842)	..	0·06	0·05	0·012	0·166	0·028	0·036	0·031	0·032	0·22	0·36	14·08	15·68	8·20	8·76	165	124	12·1	2·8	51	10	49	41
A 9	65	(1842)	3	0·06	0·07	0·020	0·020	0·029	0·037	0·028	0·023	0·39	0·46	14·06	16·15	8·72	9·20	165	124	0	1·3	61	0	50	50
A10	73	1833	2	0·07	0·05	0·009	0·18	0·023	0·023	0·034	0·032	0·24	0·37	13·10	14·52	8·80	8·95	165	124	14	2·7	47	11	40	49

* Temperatures in brackets are obtained by extrapolation

period, as well as during the oxidation period, is shown by the CaO and MgO figures to have come from the hearth. The silica balance (excluding possible roof drip) confirms this. The apparent increase in the iron content of the slag during reduction is directly contrary to physico-chemical theory which predicts that, since oxides of iron are less stable than either the oxides of chromium or manganese, the reduction of iron should take place prior to that of Mn and Cr. The fact that this is apparently not so may be explained by the possible ' fixing ' of the iron oxides either by CaO in the form of the calcic ferrites or by SiO_2 in the form of iron silicates.

This explanation is tentative only, and more slag data are being collected.

CONCLUSIONS

The chemical mechanism of the oxidation of carbon, silicon, chromium, and manganese from a bath of stainless steel with an oxygen blast is at present only partially understood. The results available from Edgar Allen and Co., Ltd., show that the way in which oxidation will proceed during blowing depends upon two main factors—starting temperature, and initial silicon content. Silicon exerts a ' protective ' action on both carbon and chromium and enables the temperature to be raised rapidly. This is an advantage initially but may be offset later by the difficulty of reducing the chromium from a slag high in silica, at any rate with ferro-silicon. The use of aluminium might prove an advantage in these cases. With the accumulation and examination of further data, a clearer understanding of the principles involved should become possible ; work on these lines is proceeding.

Acknowledgments

The authors wish to acknowledge the co-operation of Mr. Elliott and Mr. Gardner, of Messrs. Edgar Allen and Co., Ltd., and of Mr. Jeffes, of B.I.S.R.A, who gave advice regarding the chemistry of the process.

The authors also wish to thank the Directors of Messrs. Edgar Allen and Co., Ltd., for their interest in the subject and their permission to publish these data.

References

1. U.S. Patent 1,512,735.
2. U.S. Patent 1,570,229.
3. U.S. Patent 2,226,967.
4. J. H. EISAMAN : *Steel*, 1948, vol. 123, Aug. 16, pp. 112–121.
5. R. FISCHER : *Stahl und Eisen*, 1950, vol. 70, pp. 10–19.
6. D. C. HILTY : *Transactions of the American Institute of Mining and Metallurgical Engineers*, 1949, vol. 185, pp. 91–95 ; *Journal of Metals*, 1949, Feb., pp. 91–95.
7. H. J. T. ELLINGHAM : *Journal of the Society of Chemical Industry*, 1944, vol. 63, pp. 125–133.
8. F. D. RICHARDSON and J. H. E. JEFFES : *Journal of The Iron and Steel Institute*, 1948, vol. 160, pp. 261–270.
9. H. M. CHEN and J. CHIPMAN : *Transactions of American Society for Metals*, 1947, vol. 38, pp. 70–112.
10. D. CLARK : *Proceedings of the Electric Furnace Steel Conference*, 1946, vol. 4, pp. 134–135.
11. F. KÖRBER and W. OELSEN : *Mitteilungen aus dem Kaiser-Wilhelm Institut für Eisenforschung zu Düsseldorf*, 1935, vol. 17, pp. 231–245.

Oil Burning

TIP-ATOMIZING BURNERS IN THE OPEN-HEARTH FURNACE

By A. L. Cude, B.Sc., and J. R. Hall

SYNOPSIS

Trials have been carried out on a production furnace to compare two types of tip-atomizing burner, designed to give control over atomization and flame shape, with the standard back-end atomizing burner. No significant differences in either furnace performance or fuel consumption were found.

In all cases the same oil-flow rates and steam/oil ratios were required for smooth operation. It is suggested that the quantity of steam was the controlling factor in combustion, and that burner design was of minor importance.

As a result of a survey of oil-burning practice in a number of steelworks,* it was concluded that the burners currently in use in the open-hearth furnace gave little control over the characteristics of the flame. It was accordingly decided to start some experimental work, with the object of obtaining a greater degree of control over the shape, velocity, and distribution of the flame, particularly during charging and melting. This period represents the greater part of the working cycle, and any improvement in the melting rate would therefore have a relatively large effect on furnace performance.

* A. L. CUDE: "Oil Burning: Survey of Open-Hearth Furnace Practice in Twelve Works," Paper No. PE/A/22/48, British Iron and Steel Research Association.

DESCRIPTION OF BURNERS

Burner *A*

The burner in its original form is shown in Fig. 1. The oil was conveyed to the tip of the burner through a central tube, supported near the tip by a ring clamped between the outer steam nozzle and the burner body. Steam passed through the burner outer tube, and then through holes in the oil tube supporting ring to the steam nozzle. Atomization took place outside the nozzle, so that there could be no interference with the formation of the atomized

Paper PE/A/57/49 of the Fuel Committee of the Plant Engineering Division of the British Iron and Steel Research Association, received 2nd March, 1950. The views expressed are the authors' and are not necessarily endorsed by the Committee as a body.

Mr. Cude is on the staff of the Plant Engineering Division of the British Iron and Steel Research Association, and Mr. Hall is with the Shelton Iron Coal and Steel Company, Ltd.

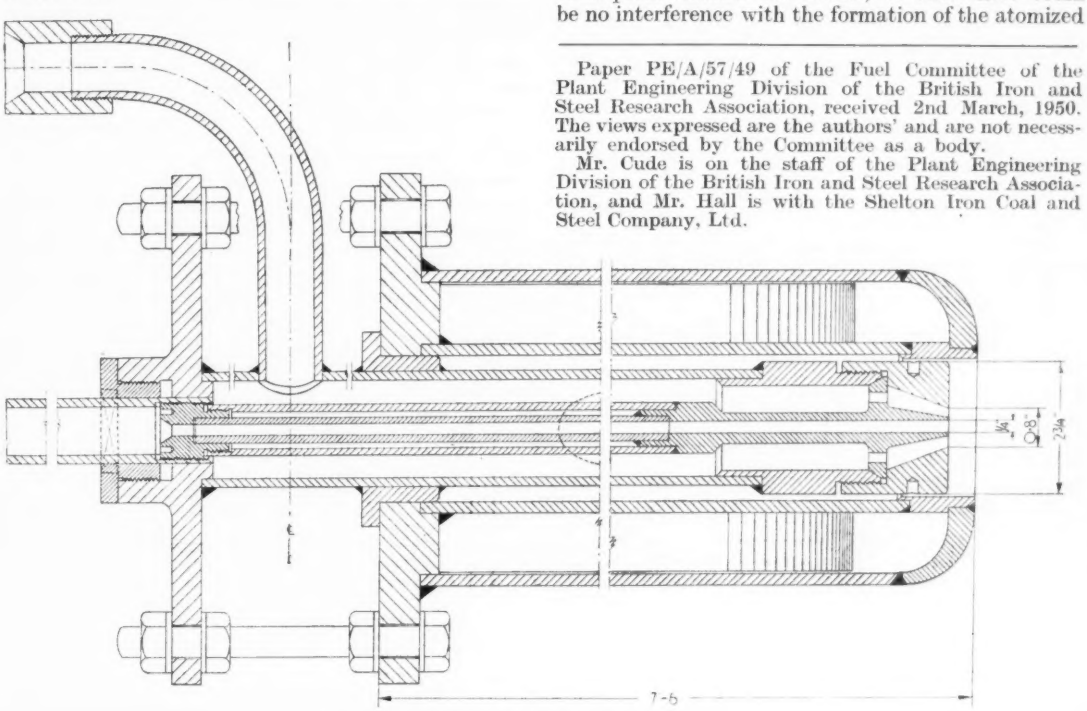


Fig. 1—Burner *A*, original arrangement

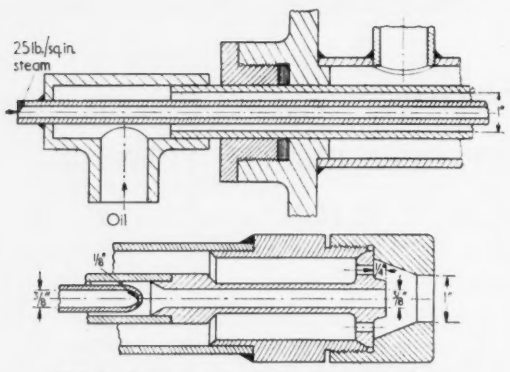


Fig. 2—Burner *A*, modified arrangement

spray by impingement on the burner walls. Stainless steel was used for the burner head, and mild steel for the inlet tubes.

For controlling the shape of the flame, three steam nozzles with cone angles of 40°, 80°, and 120° were made, to vary the angle of impingement of the steam on the oil. In addition, alternative oil-tube units were made, one with steam holes in the supporting ring parallel to the axis and the other with oblique holes to set up rotation in the steam jet.

To reduce heat transfer between steam and oil, the oil tube was encased in a sheath with a layer of asbestos tape in the annular space. The whole burner fitted loosely into a protecting water jacket having the same external form and dimensions as a standard burner, so that the two were readily interchangeable. The burner was secured to the outer end of the water jacket, and could be withdrawn easily without disturbing the jacket.

During preliminary tests a number of defects were discovered:

(1) The oil nozzle was subject to coking and became blocked in a few hours

(2) The pressure drop through the oil tube at full flow was excessive

(3) The appearance of the root of the flame suggested that atomization was very poor and that the oil was not uniformly dispersed in the jet

(4) Leakage was found in the oil-tube insulating jacket, which had proved difficult to construct because of space limitations.

To overcome these difficulties, modifications shown in Fig. 2 were made. The oil nozzle was shortened to within $\frac{1}{4}$ in. of the face of the supporting ring, so that atomization took place within the nozzle. The oil nozzle was bored out to $\frac{3}{8}$ in. diameter and the supply pipe was increased to 1 in. diameter, without insulation. A small-bore tube was passed down the centre of the oil tube and connected through a non-return valve to a 25-lb./sq. in. steam main. This valve was normally closed, but on shutting down the oil supply the valve allowed a small flow of steam to purge the burner. With this arrangement, continuous operation for several weeks without any sign of fouling was achieved.

It was found that steam flow through the swirling burner was inadequate, probably because the rotation of the jet tended to decrease the discharge coefficient. The flow was improved by increasing the nozzle diameter to 1 in. and increasing the size of the steam holes in the oil tube supporting collar. The nozzle of the non-swirling burners was also increased to 1 in. to keep the nozzles as nearly similar as possible.

No special arrangements for the control of the burner were necessary, the existing oil and steam control and reversing valves being employed. The operation of the low-pressure purging steam supply was automatic, and depended on the oil pressure in the burner.

Burner *B*

Burner *B* is illustrated in Fig. 3*a*. The basic principle consists in spreading the oil over a cup so that it forms a thin film and is then atomized by air or steam issuing from an annular orifice surrounding the cup. In this way, fine atomization can be achieved with a relatively small flow of atomizing steam. The steam jet was in the form of a converging cone, and the angle of divergence beyond the narrowest section of the jet could be varied by giving more or less swirl to the jet.

In the smaller burners the oil was spread entirely by the action of a vortex formed within the hollow cone of atomizing steam, but in the large burners used in these tests, spreading was assisted by passing the oil through a swirl chamber, to set up rotation. These burners were fitted with a by-pass valve, which allowed oil to discharge directly in a coarse spray without being spread to the periphery of the cup. The

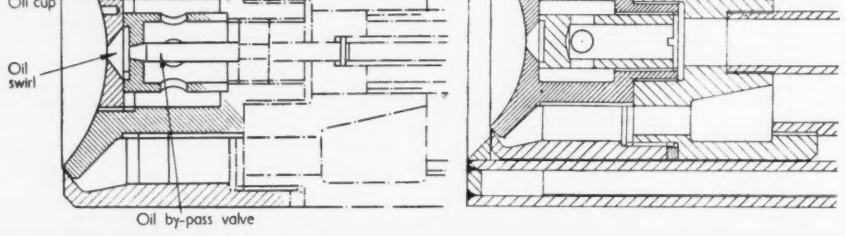


Fig. 3—Burner *B*. (*a*) Original arrangement, (*b*) modified arrangement

use of this valve, therefore, gave some control over the quality of atomization, and allowed a comparison between 'good' and 'bad' atomization.

The burners, which had a 5-in. overall diameter, were fitted into water jackets with the burner faces flush with the ends of the jacket. The oil cup and steam cap were made of a heat-resisting alloy steel. With the burner operating, cooling presented no difficulty, as the face of the burner was then completely screened with oil and steam, with sufficient heat-absorbing capacity to give adequate protection. During the other half of the cycle, with the burner off, the oil cup was exposed to the radiation of the furnace, and the heat flux falling on the face of the cup was approximately 16,000 B.Th.U./hr. To provide adequate cooling, the normal dead-end steam supply was retained while an additional quantity of steam from a low-pressure main was used to purge the oil tube and provide further cooling. This steam was supplied automatically, by a non-return valve, when the oil pressure dropped below 25 lb./sq. in. The total cooling steam flow was estimated to be approximately 200 lb./hr.

After a few days' operation a failure of the purging steam supply resulted in one of the burners becoming choked with carbon, and difficulty in cleaning was experienced because the threads of the central plug giving access to the oil swirl chamber were seized; it was also found that the thin edge of the steam cap was cracked and notched. By this time it had been discovered that the by-pass valve served no useful purpose, so the burner was rebuilt in the form shown in Fig. 3*b*. In this arrangement the burner could be dismantled from the back, and all the threads involved were well protected from heating. A new steam cap was made of ordinary steel, and was protected as much as possible by a bevelled guard ring welded into the nose of the water jacket.

This arrangement proved very satisfactory, the steam cap retaining its edge and showing no sign of burning. The oil cup was apparently adequately cooled, but probably had a fairly high skin temperature, as carbon and fume deposits formed on it rapidly: cleaning was necessary at two-day intervals. Considering the smallness of the oil and steam orifices, very little difficulty was experienced from fouling. Such difficulty as was encountered could have been greatly reduced by designing the burner for automatic withdrawal when not in use. This would have been quite practicable, but it was felt that the mechanism required was not justified for a comparatively short test.

DESCRIPTION OF FURNACE

The tests were carried out on a fixed furnace having the following dimensions:

Length of bath	27 ft. 3 in.
Length between burner tips	36 ft.
Width	15 ft. 1½ in.
Hearth area	255 sq. ft.
Nominal capacity	75 tons
Number of doors	3

The block ends are relatively short, and the burner is inserted through a small block of brickwork projecting 2½ ft. from the end wall. The roof is straight between short ramps over the blocks. There is an air port 3 ft. 8 in. long and 3 ft. 1 in. wide, on each side of the burner block.

The burner normally employed is fitted with a conventional back-end atomizer, and can then be considered representive of back-end atomizing burners, as there is little difference in performance between the several designs in current use.*

Instruments and controls are grouped together on a panel facing the furnace, and comprise the following:

Instruments—Oil flow indicator and recorder
Steam flow recorder
Air flow indicators and recorders
Roof temperature recorder
Furnace pressure recorder
Draught gauge
Oil temperature indicator
Oil and steam pressure gauges for each end of the furnace
Reversal timer with warning lamp

Controls—Gate-type control valves for oil and steam for each end
Plug type reversing valves for oil and steam linked to a common reversing handle (independently operated for each end)
Air butterfly damper control
Draught damper control
Valves for hydraulic reversing gear
Automatic furnace pressure controller (operated only during some of the periods covered by this report)

NORMAL FURNACE OPERATION

Charge—48–52 tons miscellaneous scrap
25–30 tons hot metal direct from the blast furnace

Average Firing Rates During Charging

Oil	320 gal./hr.
Steam	1600 lb./hr.
Steam/oil ratio	5 lb./gal.

Average Firing Rates During Refining

Oil	160 gal./hr.
Steam	750 lb./hr.
Steam/oil ratio	4·7 lb./gal.

Steam Supply Pressure—120 lb. sq. in.

Steam Superheat—40° F.

Air Input at Fans—500,000 cu. ft./hr., constant throughout charge.

Type of Steel Made—Rail and structural steels: the steel is melted dead soft and recarburized in the ladle.

TEST PROCEDURE

Initially, an experimental burner was installed at one end of the furnace only. This allowed direct visual comparision of the experimental flame with that of a standard burner having a conventional back-end atomizer. In addition, the standard flame could keep the furnace working fairly well if difficulty were experienced with the experimental burner. When satisfactory operation of this burner was achieved, the second burner was installed in the other end and the furnace operated for a period, to give about 20 casts. This test period was then compared with a period of normal operation by means of control charts

* A. L. CUDE: *loc. cit.*

for charging time, melting time, charging plus melting time, start charge to tap time, and total time.

The control chart consists of a central line, representing the mean value of the data, and two pairs of limit lines. The inner limits are 1·96 times and the outer limits 3·09 times the standard deviation above and below the mean value. The individual points are plotted on the chart ; if they are normally distributed about the mean, and form a homogenous population, then it is probable that not more than 1 point in 20 will lie outside the inner limits, nor more than 1 in 500 outside the outer limits.

To compare two sets of data, one set is used to establish the chart, and the other set is plotted on it. Whether the two sets of data belong to the same or different populations can then be judged from the distribution of the second set of data about the chart mean, and the proportion of points lying outside the limits. The advantages of using a chart instead of the formal methods of statistical analysis are, firstly, a reduction of labour, since it is not necessary to calculate the standard deviation of the second set of data, and secondly, a clearer indication of what is happening when the formal method of analysis gives an inconclusive result of low statistical significance.

RESULTS

Visual observation of the flame, assisted by photographs and high-speed cine-photography, established the following facts :

Burner *A*

(*a*) The different cone angles of the steam nozzles had no apparent effect on the shape of the flame.

(*b*) The swirling experimental burner had a wider angle of spread than the standard burner. Figures 6*a* and *b* show the two burners under comparable conditions when the flame cone angles were respectively 36° and 16° approximately.

The flame appeared to be slightly thicker than usual at the first door ; it was less stable and subject to pulsations.

(*c*) The non-swirling jet had a slightly greater initial angle of spread than the standard burner. Figures 6*c* and *d* show the two burners under comparable conditions when the flame cone angles were respectively 25° and 19° approximately.

The experimental flame was slightly thicker at the first door, but the difference was not very marked. Precise measurement of the angle of spread was difficult, even from a photograph, as the edge of the flame was not sharply defined.

(*d*) Both tip-atomizing burners appeared to have shorter and less dense ' black cores ' than the standard burner, implying finer droplets and consequently more rapid vaporization of the oil.

(*e*) The length of flame of both experimental burners could be altered by changing their steam/oil ratios ; in this respect they were similar to the standard burner.

General views of the flames as seen through the first door, looking obliquely towards the burner, are shown in Figs. 7 and 8.

Burner *B*

Preliminary experiments were made with two different steam swirls and with no swirl. The effect of the different swirls is more fully discussed in the Appendix, which describes some experiments made with steam and water.

(*a*) With no swirl, the initial angle of spread of the jet was of the same order as that given by the standard burner, but the initial black core was not so marked.

(*b*) The larger of the two steam swirls, illustrated in Fig. 9, gave an initial angle of spread of about 40°.

(*c*) The lower edge of this flame was parallel to, and just clear of, the apron below the burner. The bath was well covered at the first door, where the flame was much thicker than that of the standard burner. The upper surface of the flame was deflected downwards by the air stream, and was not dangerously close to the roof ; neither did there appear to be excessive impingement on the linings.

(*d*) There was no interference between the steam and oil flow, so that smoother control was possible. The oil pressure shown on the panel gauge, measured between the control valve and the furnace, was a function of the oil flow only. It was therefore a useful auxiliary to the oil flowmeter, which had a slow response to a change in the oil flow. Curves of steam and oil pressures *versus* flow rates are shown in Fig. 4.

(*e*) When the oil-swirl by-pass valve on the burner was opened, a lower oil pressure was required for a given flow rate. The oil was then discharging in a coarse jet directed along the axis of the steam jet, and it may be presumed that the atomization was much inferior to that obtained in normal operation. There was, however, no observable difference in the length of the flame.

(*f*) When operating without steam the burner was essentially a pressure jet atomizer, although the discharge velocity was not high enough for fine atomization. When the oil valve was shut off, the burner operated in this way for about three seconds while the remaining oil was cleared

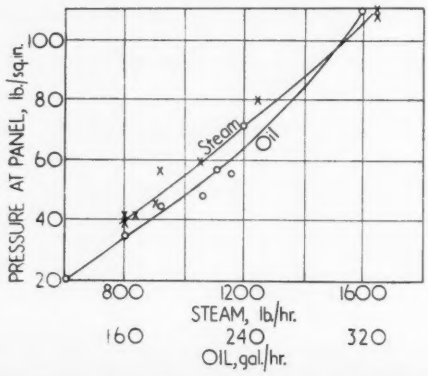


Fig. 4—Pressure/flow rate curves, Burner *B*

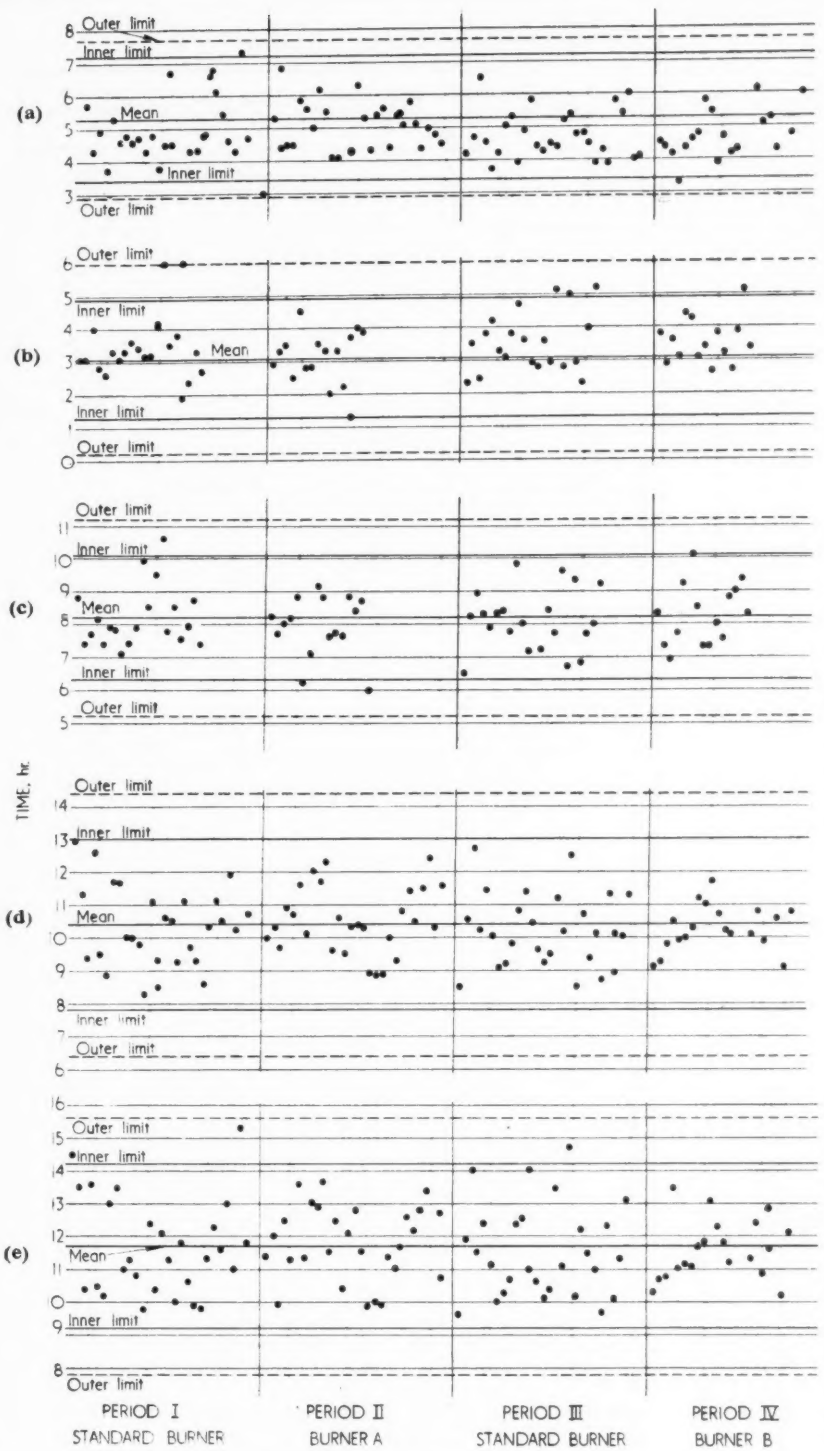


Fig. 5—Control charts for (*a*) charging time, (*b*) melting time, (*c*) charging plus melting time, (*d*) start charge to tap time, (*e*) total time

out by the purging steam. Under these conditions the oil burnt cleanly without smoke or sparks, but the flame was voluminous, shapeless, and rose to the roof. The combustion air flow was normal, since there was always a delay of a few seconds between shutting off the burner and the operation of the air valve.

(*g*) The length of the flame was determined solely by the steam/oil ratio, similarly to the standard burner.

(*h*) The initial black core was short and clearly defined, and the ignition zone was stable at all flow rates.

Furnace Performance

There was no change in metallurgical practice during the period of the tests, so that the times for the various stages of each charge can be taken as a measure of performance. Control charts have been prepared, as follows:

Fig. 5*a* Charging time
Fig. 5*b* Melting time
Fig. 5*c* Charging plus melting time
Fig. 5*d* Start charge to tap time
Fig. 5*e* Total time.

These charts are based on data from 80 casts made during a period of about six weeks' operation, using the standard burners.

Since the melting time is dependent on the melter's judgment of the time of clear melt, which is not clearly defined in the case of low-carbon melts, all casts with less than 0·15% carbon at clear melt have been excluded when preparing the charts of melting and charging plus melting time. Data for all casts are given in Tables I–IV.

Table I

BASIC DATA USED TO ESTABLISH CONTROL CHARTS

Date	Ref. No.	Charging Time, hr.	Melting Time, hr.	Charging Plus Melting Time, hr.	Start Charge to Tap Time, hr.	Total Time, hr.	Carbon at Clear Melt, %
30/1/49	1	5·8	3·2	9·0	9·9	11·0	0·19
	2	5·6	2·1	7·7	9·6	11·3	0·55
	3	5·6	3·7	9·3	10·2	11·4	0·36
	4	5·5	2·4	7·9	9·5	10·5	0·43
	5	5·2	2·8	8·0	9·4	10·3	0·44
	6	5·3	2·3	7·6	9·1	10·1	0·55
	7	4·8	2·7	7·5	9·3	10·3	0·43
	8	5·8	2·3	8·1	10·7	13·2	0·10
	9	5·6	2·1	7·7	10·1	11·3	0·89
	10	5·9	2·3	8·2	8·8	10·0	0·24
	11	6·4	2·8	9·2	11·8	12·8	0·15
	12	5·5	2·3	7·8	12·0	13·0	0·88
	13	7·3	2·3	9·6	11·5	13·3	0·55
	14	4·7	2·8	7·5	10·1	10·8	0·90
5/2/49	15	5·0	2·8	7·8	9·5	10·8	0·27
	16	7·3	3·8	11·1	11·6	12·6	0·09
	17	4·8	6·5	11·3	11·8	12·7	0·11
	18	6·8	3·0	9·8	11·8	13·3	0·10
	19	4·8	3·1	7·9	10·8	11·8	0·55
	20	4·9	2·8	7·7	10·6	12·1	0·20
	21	5·2	2·7	7·9	9·9	13·0	0·52
	22	6·1	5·3	11·4	10·4	11·4	0·25
	23	4·3	3·3	7·6	8·4	9·5	0·23
	24	5·8	3·4	9·2	11·3	13·0	0·09
	25	8·0	3·0	11·0	12·0	13·6	0·08
	26	5·3	2·2	7·5	8·5	9·7	0·22
12/2/49	27	5·4	4·4	9·8	11·2	12·5	0·07
	28	5·3	3·3	8·6	9·4	10·4	0·10
	29	4·8	2·9	7·7	9·5	10·7	0·58
	30	5·9	2·9	8·8	10·7	11·5	0·12
	31	5·9	6·5	12·4	13·7	15·0	0·09
	32	4·1	6·8	10·9	12·5	13·8	0·44
	33	5·2	2·7	7·9	9·1	11·8	0·14
	34	5·1	4·0	9·1	11·8	13·1	0·09
	35	6·0	2·4	8·4	12·1	13·2	0·39
	36	6·6	2·1	8·7	11·0	14·3	0·12
	37	4·9	3·2	8·1	10·1	15·0	0·38
19/2/49	38	4·3	6·5	10·8	12·6	14·3	0·08
	39	8·0	4·0	12·0	12·9	14·5	0·07
	40	5·7	3·1	8·8	11·3	13·5	0·22
	41	4·3	3·1	7·4	9·4	10·4	0·72
	42	4·9	5·6	10·5	12·6	13·6	0·08
	43	3·7	4·0	7·7	9·5	10·5	0·49
	44	5·3	2·8	8·1	8·9	10·2	0·19
	45	4·6	6·2	10·8	11·7	13·0	0·07
	46	4·8	2·6	7·4	11·7	13·5	0·28
	47	4·6	3·3	7·9	10·0	11·0	0·24
	48	4·7	3·1	7·8	10·0	11·3	0·82
	49	4·5	3·3	7·8	9·8	10·8	0·71
	50	4·3	3·5	7·8	8·3	9·8	0·12
	51	4·8	3·2	8·0	11·1	12·4	0·12
26/2/49	52	3·8	3·6	7·4	9·3	10·4	0·36
	53	4·5	3·4	7·9	10·6	12·1	0·58
	54	6·7	3·2	9·9	10·5	11·3	0·20
	55	5·3	3·2	8·5	9·3	10·0	0·24
	56	5·3	5·0	10·3	11·1	11·8	0·09
	57	4·3	4·6	8·9	9·7	10·6	0·14
	58	4·3	4·3	8·6	9·3	9·9	0·10
	59	4·8	3·2	8·0	8·6	9·8	0·08
	60	6·6	2·8	9·4	10·3	11·3	0·08
	61	6·1	4·2	10·3	11·1	12·3	0·07
	62	5·4	4·1	9·5	10·5	11·6	0·30
	63	4·6	6·0	10·6	11·9	13·0	0·30
	64	4·3	3·5	7·8	10·2	11·0	0·28
	65	7·3	4·6	11·9	14·0	15·3	0·07

Table I—*Continued*

Date	Ref. No.	Charging Time, hr.	Melting Time, hr.	Charging Plus Melting Time, hr.	Start Charge to Tap Time, hr.	Total Time, hr.	Carbon at Clear Melt, %
5/3/49	66	4·7	3·8	8·5	10·7	11·8	0·90
	67	4·8	4·1	8·9	9·7	10·7	0·09
	68	5·6	1·9	7·5	8·9	9·9	0·62
	69	5·8	4·9	10·7	12·9	14·0	0·08
	70	5·5	2·4	7·9	10·6	11·6	0·57
	71	5·4	3·3	8·7	10·3	11·3	0·68
	72	4·7	2·7	7·4	8·7	9·6	0·44
	73	4·7	2·8	7·5	9·3	10·3	0·76
	74	4·6	2.3	6·9	8.8	9.7	0·65
	75	4·8	2·5	7·3	9·4	10·4	0·65
	76	5·3	2·3	7·6	9·8	10·6	0·95
	77	5·1	2·9	8·0	9·9	10·8	0·60
	78	3·7	3·1	6·8	9·3	10·3	0·88
	79	4·5	2·4	6·9	8·8	9·8	0·48
12/3/49	80	5·3	2·3	7·6	9·8	10·8	0·52
Total Number		80	51*	51*	80	80	
Mean, hr.		5·3	3·1	8·2	10·4	11·7	
Standard Deviation, hr.		0·78	0·93	0·98	1·3	1·3	
Inner Limits, hr.		7·2 3·4	4·9 1·3	10·1 6·3	13·0 7·8	14·2 9·2	
Outer Limits, hr.		7·7 2·9	6·0 0·2	11·2 5·2	14·4 6·4	15·6 7·8	

* Excluding casts with less than 0·15% carbon at clear melt

Table II—FURNACE PERFORMANCE WITH BURNER *A*

Date	Ref. No.	Charging Time, hr.	Melting Time, hr.	Charging Plus Melting Time, hr.	Start Charge to Tap Time, hr.	Total Time, hr.	Carbon at Clear Melt, %
15/5/49	1	5·3	2·9	8·2	10·0	11·4	0·45
	2	6·8	2·4	9·2	10·3	12·0	0·08
	3	4·4	3·3	7·7	8·7	9·9	0·22
	4	4·5	4·8	9·3	10·9	12·5	0·08
	5	4·5	3·5	8·0	10·7	11·3	0·90
	6	5·8	4·5	10·3	11·6	13·6	0·06
	7	5·6	2·5	8·1	10·1	11·3	0·55
	8	5·0	5·9	10·9	12·0	13·0	0·05
	9	6·2	4·5	10·7	11·7	12·9	0·07
	10	5·5	5·5	11·0	12·3	13·7	0·08
	11	4·1	4·7	8·8	9·6	11·5	0·36
	12	4·1	4·3	8·4	10·6	12·5	0·10
	13	3·4	2·8	6·2	9·5	10·4	0·94
22/5/49	14	4·3	2·8	7·1	10·3	12·1	0·60
	15	6·3	2·8	9·1	10·4	12·8	0·19
	16	5·3	3·5	8·8	10·3	11·5	0·43
	17	4·3	3·3	7·6	8·9	9·9	0·42
	18	5·4	2·6	8·0	8·9	10·0	0·10
	19	5·6	2·0	7·6	8·9	9·9	0·29
	20	4·4	3·3	7·7	10·0	11·3	0·23
	21	5·4	2·2	7·6	9·3	11·0	0·54
	22	5·1	4·4	9·5	10·8	11·7	0·12
	23	5·8	4·3	10·1	11·4	12·6	0·08
	24	5·1	3·7	8·8	11·1	12·2	0·55
	25	4·4	4·0	8·4	11·5	12·8	0·80
	26	5·0	6·3	11·3	12·4	13·4	0·07
	27	4·8	3·9	8·7	10·3	11·7	0·45
29/5/49	28	4·5	5·0	9·5	11·6	12·7	0·11
Total Number		28	16*	16*	28	28	
Mean, hr.		5·0	3·2	8·0	10·5	11·8	
Standard Deviation, hr.		0·85	0·70	0·76	1·06	1·13	

* Excluding casts with less than 0·15% carbon at clear melt

Table III

SECOND PERIOD OF OPERATION WITH STANDARD BURNERS

Date	Ref. No.	Charging Time, hr.	Melting Time, hr.	Charging Plus Melting Time, hr.	Start Charge to Tap Time, hr.	Total Time, hr.	Carbon at Clear Melt, %
21/8/49	1	4·2	2·3	6·5	8·5	9·6	0·42
	2	4·7	3·5	8·2	10·5	11·9	0·60
	3	6·5	2·4	8·9	12·7	14·0	0·51
	4	4·5	3·8	8·3	10·2	11·5	0·58
	5	3·7	4·2	7·9	11·4	12·4	1·23
	6	4·2	3·9	8·1	10·0	11·1	0·09
	7	5·0	3·3	8·3	9·1	10·0	0·20
	8	5·3	3·1	8·4	9·2	10·3	0·30
	9	3·9	3·8	7·7	9·8	10·7	0·72
	10	4·9	4·9	9·8	10·8	12·4	0·18
	11	5·8	3·8	9·6	11·4	12·5	0·09
	12	4·4	3·6	8·0	10·4	14·0	0·46
	13	4·3	2·9	7·2	9·6	10·6	0·62
28/8/49	14	4·5	4·2	8·7	9·2	10·1	0·09
	15	4·4	2·8	7·2	9·5	10·4	0·71
	16	5·2	2·9	8·1	11·2	13·5	0·09
	17	5·4	3·8	9·1	10·2	11·1	0·10
	18	4·8	3·6	8·4	12·5	14·7	0·26
	19	4·8	2·9	7·7	8·5	10·2	0·25
	20	4·5	5·1	9·6	10·7	12·2	0·20
	21	3·9	2·8	6·7	9·4	11·5	1·01
	22	4·3	5·0	9·3	10·1	11·0	0·20
	23	3·9	2·9	6·8	8·7	9·7	0·55
	24	5·8	3·7	9·5	11·3	12·3	0·07
	25	5·4	2·3	7·7	8·9	10·1	0·19
	26	6·0	4·5	10·5	13·0	19·0	0·07
	27	4·0	4·0	8·0	10·0	11·3	0·68
3/9/49	28	4·1	5·2	9·2	11·3	13·1	0·15
Total Number		28	21*	21*	28	28	
Mean, hr.		4·7	3·5	8·1	10·5	11·2	
Standard Deviation, hr.		0·71	0·92	0·93	1·21	2·59	

* Excluding casts with less than 0·15% carbon at clear melt

The various sections of the chart are :

Period I—28 of the 80 casts made during a period of normal operation with standard burners

Period II—28 casts operating with burner *A*

Period III—28 casts during a second period of normal operation

Period IV—19 casts operating with burner *B*.

Automatic furnace pressure control was in operation during periods *III* and *IV*.

Fuel Consumption

It was only possible to obtain weekly averages of fuel consumption, and although there was a general trend towards a slight improvement during the test periods, this was common to all furnaces in the shop.

DISCUSSION OF RESULTS

Furnace Performance

Charging Time—There is a general trend towards values below the control mean (*see* Fig. 5*a*) and in periods *III* and *IV* the majority of the points are below the mean. Only one point falls outside the inner control limits.

Melting Time—There is a trend towards values above the control mean (*see* Fig. 5*b*) and in periods *III* and *IV* the proportion of points outside the inner control limits is more than 1 in 20 (1 in 7 and 1 in 15 respectively). This, however, is not highly significant.

Melting plus Charging Time—In all periods a very uniform distribution is obtained (*see* Fig. 5*c*) and it is apparent that any tendency to a decrease in charging time is offset by a corresponding increase in melting time.

Start Charge to Tap Time and *Total Time*—In all periods not more than 1 in 20 of the points lies outside the inner control limits, and distribution about the mean is normal (*see* Figs. 5*d* and *e*.)

These control charts indicate that there is no difference in performance between the burners.

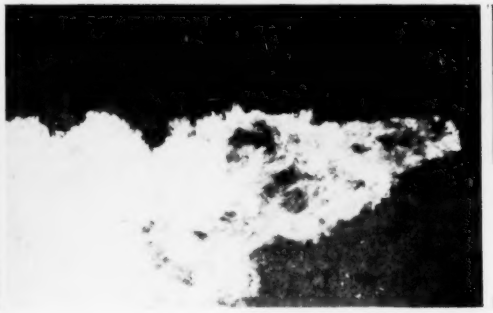
Atomization and Flame Length

While the evidence for differences in atomization is not conclusive, because no direct measurements of drop sizes were made, experience of burner design suggests that burner *B* should be a far better atomizer than either burner *A* or the standard burner. This is supported by the appearance of the initial black cores, on the reasonable assumption that the length of the core depends upon drop size.

In spite of differences in the initial angle of spread, and the length of the black core, no difference could be detected in the total length of the flame at similar oil and steam flows, even when in burner *B* the atomization was debased by opening the oil-swirl by-pass valve.

(*a*) Standard burner. Oil, 200 gal./hr. ; steam, 800 lb./hr.

(*b*) Burner *A*, swirling form. Oil, 180 gal./hr. ; steam, 800 lb./hr.



(*a*) Swirling form

(*b*) Non-swirling form

Fig. 7—Oblique views of Burner *A* through first door of furnace

(*c*) Standard burner. Oil, 296 gal./hr. ; steam, 1540 lb./hr.

(*d*) Burner *A*, non-swirling form. Oil, 296 gal./hr.; steam, 1540 lb./hr.

Fig. 6—Standard and experimental burner flames

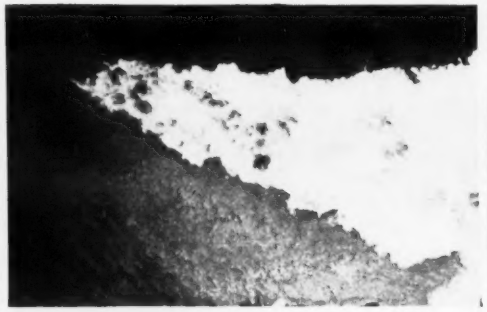


Fig. 8—Oblique view of standard burner through first door of furnace

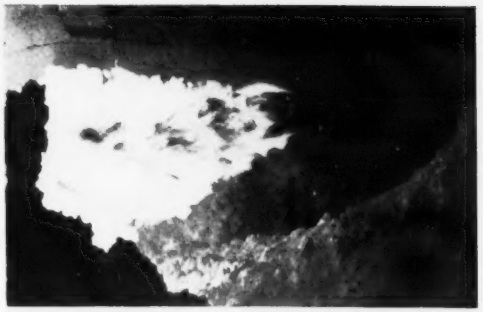


Fig. 9—Burner *B*. Oil, 120 gal./hr. ; steam, 800 lb./hr.

[*Crude and Hall*
[*To face p.* 426

(*a*) Water only, 50 lb./sq. in. ; cone angle, 85°

(*b*) Steam only, 30 lb./sq. in. ; medium swirl, cone angle, 37°

(*c*) Steam, 30 lb./sq. in., no swirl ; water, 35 lb./sq. in. ; cone angle, 17°

(*d*) Steam, 30 lb./sq. in., narrow angle swirl ; water, 35 lb./sq. in. ; cone angle, 44°

(*e*) Steam, 30 lb./sq. in., medium swirl ; water, 35 lb./sq. in. ; cone angle, 40°

(*f*) Steam, 30 lb./sq. in., wide angle swirl ; water, 35 lb./sq . in. ; cone angle, 43°

Fig. 10—Steam-water jets from burner *B*

Table IV

FURNACE PERFORMANCE WITH BURNER *B*

Date	Ref. No.	Charging Time, hr.	Melting Time, hr.	Charging Plus Melting Time, hr.	Start Charge to Tap Time, hr.	Total Time, hr.	Carbon at Clear Melt, %
28/6/49	1	4·5	3·8	8·3	9·1	10·3	0·34
	2	4·4	2·9	7·3	9·3	10·7	0·61
	3	4·2	3·4	7·6	9·8	10·8	0·11
	4	3·3	3·6	6·9	10·5	13·5	0·76
	5	4·3	4·0	8·3	9·9	11·0	0·09
	6	4·6	3·1	7·7	10·0	11·2	0·70
	7	4·8	4·4	9·2	10·3	11·1	0·32
	8	5·8	4·3	10·1	11·2	11·7	0·41
	9	5·4	3·1	8·5	11·6	11·8	0·75
	10	3·9	3·4	7·3	11·7	13·1	0·82
	11	4·7	2·6	7·3	11·3	12·3	1·07
	12	4·2	3·8	8·0	10·2	11·8	0·44
4/7/49	13	4·3	3·2	7·5	10·1	11·2	0·74
6/9/49	14	6·1	2·7	8·8	10·1	11·3	0·28
	15	5·1	3·9	9·0	10·8	12·4	0·30
	16	5·3	3·8	9·1	9·9	10·9	0·12
	17	4·3	5·1	9·4	10·6	11·6	0·82
	18	4·9	3·4	8·3	9·1	10·2	0·26
9/9/49	19	6·0	6·0	9·5	10·8	12·1	0·08
Total Number		19	15*	15*	19	19	
Mean, hr.		4·7	3·6	8·2	10·3	11·5	
Standard Deviation, hr.		0·73	0·68	0·93	0·77	0·87	

* Excluding casts with less than 0·15% carbon at clear melt

For satisfactory operation of the furnace it was found that oil-flow rates and steam/oil ratios were the same for all the burners. From this it would appear that the steam jet has an important function in obtaining an adequate combustion rate, and also in controlling the aerodynamics of the flame, which are of much greater significance than control of atomization by burner design.

The oil swirl in burner *B* is in principle a pressure-jet type of atomizer. On reversals, after shutting off the atomizing steam and closing the oil valve, the residual oil in the burner line was cleared by low-pressure steam. For a few seconds, therefore, oil was entering the furnace in a wide-angle spray from a low-pressure atomizer, the discharge velocity of which was too low for good atomization. Nevertheless the oil burned cleanly without smoke or sparks, showing that atomization was adequate; but the flame was voluminous, shapeless, and rose to the roof. This suggests that a purely pressure-atomizing burner would be impracticable in an open-hearth furnace, without adequate control of the combustion air flow.

Flame Shape

By applying more swirl to the jet the angle of spread could be increased, and with an angle of 40° there appeared to be maximum coverage of the bath without undue impingement on the linings. The flame was much thicker opposite the first door than was that of the standard burner, a condition which should increase radiation from the flame. There was no evidence in the control charts that this made any change in the furnace performance, but the melters considered that the wider flame was slower for cutting down scrap.

Burner Maintenance

Burner *A*, in its modified form, gave no difficulty from fouling, and appeared able to run for long periods without cleaning. Cleaning was greatly simplified by the ease with which the comparatively light burner could be withdrawn from the water jacket.

There was no sign of overheating of the burner nozzle, although it was fairly large and only a loose fit in the water jacket.

Burner *B* presented more difficulty because of its larger size. The outer steam nozzle was adequately protected by the guard ring in the water jacket, but the inner cup was completely dependent on the dead-end steam for cooling. Any failure of this steam resulted in rapid and complete blocking of the oil orifice with hard coke, although there was no tendency to blockage when the purging steam supply was adequate. Coke and fume deposits formed on the oil cup, and it was necessary to clean the burner every two days. A burner of this type should be withdrawn from the furnace when not in operation: the design of an automatic apparatus for this purpose would present no difficulty, but it was not considered worth while to construct it for short-term tests.

CONCLUSIONS

The conclusions which follow were derived from trials made on a single 75-ton open-hearth furnace, and will not necessarily apply to other furnaces. The trials were too short to give any useful information regarding the life of the burners; similarly, no opinion could be formed of the influence of the burner on furnace maintenance.

(1) There is no statistical evidence for any

difference in furnace performance between the several designs of burner tested.

(2) The aerodynamics of the flame jet, determined by the steam and oil flows, are of much greater importance than any effects introduced by details of burner design.

(3) Increasing the cone angle of the jet appears to give no advantage.

(4) Atomization of the oil, within the range considered, is of negligible importance in controlling the development of the flame.

(5) A pressure-jet atomizer will not give a satisfactory flame, and the main function of the atomizing steam is to secure adequate combustion rates and flame control.

(6) No great difficulty is found in maintaining tip-atomizing oil burners in an open-hearth furnace, provided adequate protection is given by dead-end steam during the off period.

Acknowledgments

The authors express their indebtedness to the Company in whose Works the tests were carried out, for their kindness in providing facilities; to Mr. R. P. Fraser, who designed burner *B*; to the manufacturers of burner *B*, for the development and modification of the burner and for their assistance at some of the trials; to Mr. C. H. Bacon for taking the high-speed cinephotographs, and to an Oil Company which was also of great assistance.

APPENDIX

Steam-Water Jets from Burner *B*

Burner *B* gave wider angles of flame spread than the conventional back-end atomizing burner. This wider angle was obtained by setting up a swirling motion in the steam approaching the orifice, by passing the steam through slots at an angle to the axis of the burner. To obtain some small variation in the angle of flame spread, three different swirls were made with dimensions shown in Table V. In addition, the swirl element could be adjusted longitudinally with respect to the discharge orifice.

Observation of the flame in the furnace showed little difference in flame angle between swirls 1 and 2, but a much narrower flame was obtained by removing the swirl. Swirl 3 was not tried in the furnace. As the effect on the flame shape of the combustion air flow and high temperature in the furnace was not known, it was decided to carry out tests on the burner in cool, still surroundings.

Table V

DETAILS OF STEAM SWIRLS IN BURNER *B*

No. of slots, 8; Inclination of slot to axis, 60°; Ratio tangential axial velocity component, 1·73

Swirl No.	Expected Nature of Jet	Width of Slot, in.	Min. Depth of Slot, in.	Total Slot Area, sq. in.	Relative Slot Velocities*
1	Narrow	0·19	0·75	1·14	1·0
2	Medium	0·16	0·75	0·96	1·2
3	Wide	0·19	0·50	0·76	1·5

*Assumed inversely proportional to slot area

It was also found that the knife edge of the normal steam cap buckled under the severe conditions in the furnace, and the opportunity was taken to test a robust thick-edged steam cap.

Experimental Procedure

The burner was set up in a sheltered space in the open, and connected to sources of steam and water. (Water instead of oil was selected for convenience.) A photograph of the spray was taken for each test condition, and the angle of spread was measured from this photograph. The tests were arranged to determine the effect of the following variables :

Swirl design
Position of swirl
Steam flow rate
Oil flow rate
A thick edge on the steam cap.

Results

Full results are given in Table VI, and representative photographs are shown in Figs. 10*a–f*.

Steam and Water Flow Rate—Tests were made at three steam pressures and five water pressures. The water flow is a function of the pressure, and (for reasons that will be mentioned later) it is reasonable to suppose that for a given pressure the same steam flow, within narrow limits, is obtained for all swirls. Accordingly a multiple correlation of steam and water pressure with cone angle was made, and it was found that there was (*a*) no significant correlation of spray cone angle with varying water pressure, and (*b*) a highly significant correlation of spray cone angle with steam pressure.

The cone angle is plotted against steam pressure in Fig. 11, which shows that the variation is greatest at low steam pressures.

Steam Swirl Design and Position—There are no differences between the angles given by different designs of swirl, or between the extreme positions of the swirl in the burner head. With no swirl a narrow-angle jet results, similar in shape to that given by a back-end atomizing burner.

Comparison with Flame—The cone angles given under the special test conditions approximate to those obtained in the furnace.

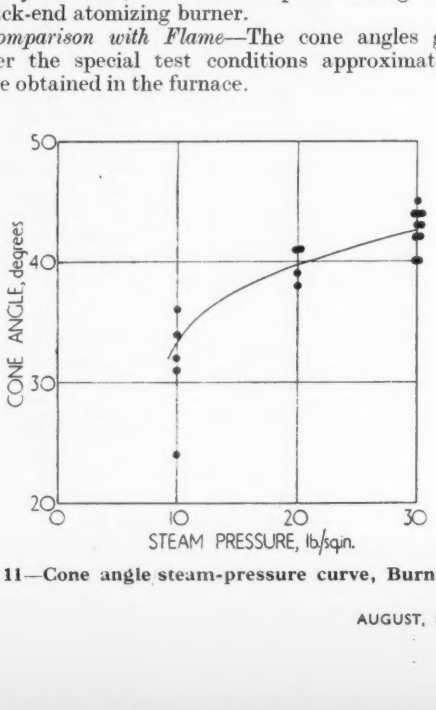


Fig. 11—Cone angle steam-pressure curve, Burner *B*

Table VI

EXPERIMENTAL DATA FOR STEAM-WATER JETS

Test Number	Swirl Number	Swirl Position	Steam Cap	Steam Pressure, lb./sq. in.	Water Pressure, lb./sq. in.	Cone Angle, Degrees
1	2	Forward	Normal	20	20	41
2	2	,,	,,	20	35	41
3	2	,,	,,	20	50	39
4	2	,,	,,	30	50	40
5	2	,,	,,	30	35	40
6	2	,,	,,	30	20	44
7	2	,,	,,	10	20	34
8	2	,,	,,	10	20	31
9	2	,,	,,	10	30	32
10	2	,,	,,	10	40	24
11	2	Forward	Normal	30	Nil	37
13	2	Back	Normal	30	35	42
14	2	,,	,,	30	35	42
15	2	Forward	Thick-edged	10	20	36
16	2	,,	,,	20	20	38
17	2	,,	,,	30	20	43
18	1	Forward	Normal	30	35	45
19	1	,,	,,	30	35	44
20	...	...	...	Nil	20	80
21	...	...	...	Nil	50	85
23	None	...	Normal	30	35	22
24	None	...	,,	30	35	17
26	3	Forward	Normal	30	35	43
27	3	,,	,,	30	35	44

Effect of Thick-edged Steam Cap—No interference from the thick edge of the cap was apparent.

Water Spray Obtained without Steam—In the absence of steam the water jet was completely broken down into a spray, but the droplet size was fairly large.

In this burner the final steam orifice was an annulus with an area of less than 0·1 sq. in. It was therefore much less than the area of the steam swirl slots, and so the pressure drop through the burner took place mainly in the final annulus. This justified the assumption that equal pressures would give equal flows with all swirls.

The critical pressure ratio for saturated steam discharging from nozzles is 0·58, so that, if the inlet pressure exceeds 26 lb./sq. in. absolute or 11 lb./sq. in. gauge, the nozzle throat pressure will be greater than atmospheric, and the discharge velocity will equal the local velocity of sound. Increased pressures result in increased mass discharge rates, by raising the pressure in the annulus, but the linear velocity will not change very much. The majority of the tests were carried out under these conditions, so it may be assumed that the conditions tested were similar to those at full flow, although the tests were made in the lower part of the working range of the burner.

Since, under critical discharge conditions, the upstream pressure is approximately proportional to the square of the discharge, and the specific volume is inversely proportional to the pressure, it follows that the volume flow in the swirl will decrease with increasing pressures and discharge rates. Also, because of the effect of the pressure and area ratios, the velocity in the swirl will be much less than the discharge velocity. These considerations may explain why the different swirls had so little relative effect. On the other hand, all three swirls produced an equally large effect compared with the jet obtained without swirl. The one factor in which the swirls differ from a non-swirling jet is the inclination of the slots to the axis of the burner : this inclination determines the ratio of the tangential to the axial velocity component, and is the same in all three swirls. It is possible, therefore, that under critical discharge conditions it is the main design factor determining the cone angle of the jet.

Determination of Silicon in Iron and Steel by an Absorptiometric Method

By the Methods of Analysis Committee

SYNOPSIS

Two modifications of an absorptiometric method for the determination of silicon, based on the reduction of silico-molybdate to molybdenum blue, have been investigated, to cover ranges from 0·05 to 2% and 0 to 0·05% of silicon, respectively. It has been shown that stannous chloride reduction is satisfactory in the higher range, but that for low-silicon contents reduction by ferrous sulphate in the presence of oxalic acid is preferable. Details of the recommended procedures and tables of results are given.

Introduction

At the first meeting of the Physico-Chemical Methods of Analysis Sub-Committee, a progress report of the Silicon–Manganese Panel, forwarded by the Analysis Sub-Committee of the Heterogeneity of Steel Ingots Committee of The Iron and Steel Institute, was considered.

Four tentative methods for the determination of silicon had been formulated, two embodying chemical procedures, which have since been modified and form the subject of a British Standard method,[1] and two employing an absorptiometric finish, further work on which is the subject of the present paper.

The constitution of the P.C.M. of A. Sub-Committee, during the period covered by this investigation was as follows :

Mr. E. J. Vaughan (*Chairman*)	Bragg Laboratory, N.O.I.D.
Mr. B. Bagshawe	Brown-Firth Research Laboratories
Mr. H. C. Davis	R.A.E., Farnborough
Mr. H. Groom	Bragg Laboratory, N.O.I.D.
Mr. S. Harrison	Kayser Ellison and Co., Ltd.
Mr. G. Murfitt	Wm. Jessop and Sons, Ltd.
Mr. A. S. Nickelson (replaced by Mr. K. Stanford, 1948)	Ministry of Supply
Mr. L. Russell	Babcock and Wilcox, Ltd.
Mr. H. G. Short	N.P.L., Teddington
Mr. G. E. Speight (replaced by Mr. G. Padget, 1948)	United Steel Companies, Ltd.
Mr. J. H. Wright (replaced by Mr. H. B. Anthony, 1948)	Dorman Long and Co., Ltd.
Mr. A. Mayer (joined 1948)	British Cast Iron Research Association
Mr. H. K. Moneypenny (joined 1948)	G.K.N. Research Laboratories

Satisfactory results had been obtained by the Panel for normal silicon ranges in steel with the familiar procedure[2,3] utilizing the silico-molybdate reaction, but the determination of very low-silicon contents (up to 0·05%) presented difficulties. Since certain steel specifications required very low-silicon limits which were not easily determined accurately by gravimetric methods, the Panel had attempted to develop a modification of the Gentry and Sherrington absorptiometric method[4] and preliminary results obtained had shown considerable promise.

The general principle of both methods was solution of the weighed sample in dilute sulphuric acid, oxidation with permanganate followed by destruction of the excess, dilution to a definite volume, and formation of molybenum blue equivalent to the silicon in one aliquot whilst treating a second aliquot for comparison purposes. The end procedure usually employed for the normal range of silicon in steel was based on the reduction of silico-molybdate to molybdenum blue by stannous chloride ; in the Gentry and Sherrington modification reduction was effected by ferrous sulphate in the presence of oxalic acid.

The Sub-Committee pointed out that the methods outlined did not include insoluble silica or silicates present in the samples for analysis, although work carried out by other Committees had shown that 0·01–0·02% of silicon in an insoluble form might be found in certain irons and steel as follows :

Steel type	Insoluble Silica as SiO_2, %	Soluble Silicon as Si, %
Manganese–molybdenum	0·03	0·14
3% nickel–chromium	0·04	0·04
Mild steel	0·02	0·06

It was appreciated that such inclusions had not the same metallurgical significance as silicon in solid solution and that, particularly in the low-silicon ranges, a knowledge of the actual silicon present in solid solution in the metal was of first importance. Provided this limitation was realized the Sub-Committee felt that the methods might prove useful, particularly for low-silicon steels.

Preliminary investigations were carried out on both methods using ferrous sulphate and hydrogen peroxide (*without* boiling to remove excess) as alternative reducing agents for the manganese dioxide produced by the permanganate oxidation.

NORMAL SILICON RANGE

Preliminary Tests

The Sub-Committee's preliminary tests revealed that certain modifications to the original method were advisable.

Nature of Reducing Agent—The use of ferrous sulphate led to general lack of reproducibility and difficulty was experienced in deciding when just

Paper MG/D/49/50 of the Methods of Analysis Committee of the Metallurgy (General) Division of the British Iron and Steel Research Association, received 13th January, 1950.

Table I

CRITICAL AMOUNTS OF REAGENTS

Water, added from cylinder, ml.	**30**	**30**	**30**	**30**	**30**	**50***
Ammonium molybdate, added from burette, ml.	**12**	**12**	**8**	**8**	**8**	**10***
Acid, added from cylinder, ml.	**20**	**20**	**20**	**20**	**20**	**20***
$SnCl_2$, added from burette, ml.	**12**	**8**	**8**	**8**	**12**	**10***
Final volume diluted with water, ml.	**110**	**110**	**110**	**110**	**110**	**110*** (assumed)
Absorption reading	**0·345**	**0·66**	**0·68**	**0·355**	**0·35**	**0·35**

* From pipette

sufficient reagent had been added. Hydrogen peroxide reduction was preferable since the addition could be controlled almost to a drop.

Final Volume of Solution—In preference to making the recommended five pipetted additions to give an assumed final volume of exactly 110 ml., it was thought that an increase in both speed and accuracy would be obtained by making the additions from fast-flowing burettes and diluting finally to exactly 100 ml. in a graduated flask, provided that the exact amounts of reagents were not sufficiently critical to prevent the adoption of a change in final volume.

A series of tests was made to determine whether the amounts of reagents were critical and to prove whether the 50-ml. addition of water before the ammonium molybdate solution was necessary, or whether approx. 30 ml. could be added, leaving the balance for final dilution to a definite volume (*e.g.*, 100 ml.). 20 ml. of a solution containing 0·50 g. of iron and 0·003 g. of silicon, diluted to 250 ml., were used and the results are given in Table I.

In all cases where the volume of stannous chloride was 10 ml. or more, the absorption readings were within the limits of accuracy of the absorptiometer; below 10 ml. they were not. It appeared that the critical limits to which the stannous chloride could be added required further investigation; the additions of other reagents to the 20-ml. aliquot were not as critical.

Critical Volume of Stannous Chloride—In order to verify this minimum addition of stannous chloride, and also to determine a possible upper critical limit, tests shown in Table II were carried out on a solution containing 0·5 g. of iron and 0·0025 g. of silicon and it was established that 10 ml. of 1% stannous chloride was the minimum volume permissible. Increased amounts of stannous chloride did not affect the analysis, although with increasing stannous chloride concentration the absorption of the blank (compensating) solution was increased.

As already mentioned, in tests on steels using the ferrous sulphate method inconsistent results were obtained. Where a large excess of potassium permanganate was used in the oxidation stage it was necessary to make correspondingly large additions of ferrous sulphate solution. Inconsistency was attributed to stannous chloride being used to reduce the additional ferric iron, leaving insufficient for reduction of the silico-molybdate. This was eliminated when ferrous sulphate was replaced by hydrogen peroxide.

Table II

DETERMINATION OF CRITICAL AMOUNTS OF STANNOUS CHLORIDE

$SnCl_2$, ml.	$FeSO_4$ Reduction			H_2O_2 Reduction		
	Test	Blank	Difference	Test	Blank	Difference
8	0·685	0·99	0·305	0·66	0·985	0·325
9	0·525	0·99	0·465	0·47	0·985	0·515
10	0·46	0·985	0·525	0·45	0·98	0·53
12	0·455	0·985	0·53	0·44	0·975	0·535
16	0·445	0·97	0·525	0·43	0·96	0·53
20	0·43	0·955	0·525	0·42	0·945	0·525

Conclusions

From the evidence provided by all members of the Sub-Committee, it was agreed that the addition of stannous chloride should be increased from 10 ml.

Table III

RESULTS OBTAINED BY FINAL METHOD (APPENDIX I)

Sample	Silicon, %								
	Analyst							Average	Gravimetric (BS 1121 : Part 10)
	A	B	C	D	E	F	G		
Cast Iron	1·70	1·78	1·79	1·78	1·73	1·71	1·77	1·75	1·74
Low-Carbon Steel	0·060	0·065	0·065	0·075	0·065	0·070	0·065	0·065	0·07
13% Cr, Stainless	0·27	0·28	0·29	0·30	0·28	0·28	0·25	0·28	0·28
18/4/1 High Speed	0·15	0·17	0·16	0·165	0·15	0·175	0·15	0·16	0·16
6% Cr, 1·5% Si	1·39	1·43	1·40	1·43	1·42	1·415	1·41	1·41	1·42
1% Carbon Steel	0·15	0·15	0·15	0·155	0·15	0·15	0·155	0·15	0·152

of a 1% to 10 ml. of a 1·2% solution; that hydrogen peroxide reduction was to be recommended; and that additions should be made to the 20-ml. aliquot to arrive at a final volume of 100 ml.

A revised draft of the method was circulated for further trials with a new series of steels and cast iron samples and the results (Table III), covering a wide range of samples of varying type, were considered highly satisfactory. After further modification of the details of the calibration procedure and some slight alteration in the standardization technique, Method 1 (described in Appendix I) was submitted to the British Standards Institution, and finally published as B.S. 1121 : Part 15.

LOW-SILICON RANGE

Preliminary Tests

The Sub-Committee's preliminary determinations on low-silicon samples, by the modification of the Gentry and Sherrington method, were not altogether satisfactory. The results are given in Table IV.

Members of the Sub-Committee had varying experiences in using the method. The high background colour due to the presence of oxalic acid was generally commented upon, being in direct contrast to that experienced in the normal silicon range method. To some members the time factor between reagent additions appeared to be somewhat critical. The following points were therefore investigated, using samples of the same mild and carbon steels, and/or synthetic solutions.

(1) Conditions of silico-molybdate formation
  (i) The necessity for a 15-min. standing period
  (ii) The adequacy of the ammonium molybdate addition in view of the amount of iron in the solution
  (iii) The temperature during the standing period.

(2) The exact time between the addition of oxalic acid and ferrous ammonium sulphate
  (i) Addition of the two reagents simultaneously
  (ii) Addition of ferrous salt immediately following the oxalic acid addition
  (iii) With different time intervals between the additions.

(3) The stability of the molybdate blue after these variations.

Table IV

PRELIMINARY RESULTS USING THE MODIFIED METHOD

Analyst	Mild Steel		Carbon Steel	
	$FeSO_4$ Reduction Si, %	H_2O_2 Reduction Si, %	$FeSO_4$ Reduction Si, %	H_2O_2 Reduction Si, %
A	0·035	0·039	0·013	0·012
B	0·038	0·038	0·013	...
	...	...	0·013	...
C	0·043	...	0·012	...
D	0·040	0·041	0·015	0·015
	0·038	0·040	0·017	0·015
	0·037	0·040	0·015	0·016
	...	0·041	0·017	0·015
E	0·027	0·027	0·015	0·018
F	0·047	0·050	0·019	0·022
G	0·050	0·050	0·022	0·021
	0·050	0·050	0·017	0·022
	0·050	0·050	0·019	0·021

Considerable experimental work was done in connection with the above suggested investigation programme and the following results are typical of those obtained by various members.

Conditions of Silico-Molybdate Formation

Standing Period—From the following readings made with a single sample, after standing for periods of 1–25 min., it was concluded that a minimum standing period of 15 min. was necessary to ensure maximum formation of silico-molybdate.

Standing Time, min.	Difference Reading
1	0·585
5	0·88
10	0·985
15	1·05
20	1·045
25	1·055

Quantity of Ammonium Molybdate—Tests were made using a solution (inclusive of blank) giving a difference reading of 0·65, and the following results were obtained :

10% Ammonium Molybdate, ml.	Difference Reading
2	0·035
5	0·42
7	0·585
8	0·62
9	0·65
10	0·655
20% Ammonium Molybdate, ml.	
10	0·625, 0·62, 0·59

When quantities of ammonium molybdate less than 10 ml. were added, the volume was made up with water.

10 ml. of reagent were shown to be sufficient; this view was confirmed by the fact that with this addition the calibration graph gave a linear relationship within the calibration limits.

Temperature—The following figures for difference readings show that the temperature of the solution during the 15-min. standing period for formation of the silico-molybdate is important. The formation of the complex is complete only above 18° C. and a temperature of 20 ± 2° C. has therefore been specified in the method.

Temp. During Standing Period, °C.	Expt. 1	Expt. 2	Expt. 3	Expt. 4
14	0·210	0·520	0·710	...
15	...	...	...	0·430
18	...	0·550	0·755	0·463
20	0·250	0·560	0·765	0·470
25	0·260	0·560	0·760	0·470

Time Between Addition of Oxalic Acid and Ferrous Ammonium Sulphate

Added Simultaneously—The two reagents were added simultaneously and the difference readings obtained were :

Control sample	0·66
,, ,,	0·66
Mixed reagents	0·715
,, ,,	0·695
,, ,,	0·725

In the case of the control sample, the ferrous ammonium sulphate was added immediately the precipitate had been dissolved by oxalic acid. The addition of a mixture of the two reagents gave a

higher and slightly erratic figure, probably owing to the ferrous solution coming into contact with precipitated molybdates.

Addition of Ferrous Ammonium Sulphate Immediately after Oxalic Acid—This method was found to give closely reproducible readings, *i.e.*, to ± 0·01 for a given sample.

With Different Time Intervals between Additions—It was found that with differing time intervals between reagent additions, different absorption values were obtained. This was verified by the following difference readings :

Time, min.	Expt. 1	Expt. 2	Expt. 3
Immediate	0·45	0·59	0·87
1	0·445	0·58	0·86
2	0·42	0·57	0·845
5	0·42	0·55	0·785
8	...	0·55	...
10	0·395	0·52	0·735
15	0·37	...	0·71

From these experiments, it will be seen that for times up to 2 min. the difference in absorption values is only 0·02–0·03. Due to the sensitivity of the method, this is equivalent only to approx. 0·002% of Si at a maximum. In practice this time should not be approached if burettes are used for making additions of reagents and if the ferrous ammonium sulphate is added immediately after the molybdates have been redissolved in oxalic acid.

Stability of the Molybdate Blue

The stability of the colour reading under ' control ' conditions was ± 0·02 over a period of 2 hr. With varying quantities of molybdate the absorption was stable at the originally produced colour for at least 30 min., which was considered to be satisfactory.

Further Investigations

It was finally decided that the 15-min. standing time after the addition of ammonium molybdate should be amended to 20 min. The Sub-Committee appreciated the desirability of presenting the method in a manner similar to that of the normal range, and a new draft method was prepared, designed to incorporate the optimum conditions which had arisen from the investigations of the Sub-Committee, and to include the principle of diluting the final coloured solution to a definite fixed volume. This draft was subjected to considerable criticism. Some members questioned the effect of the reagent blank, under the modified procedure, on the construction of the calibration graph, and whilst some found this to be a point of importance, others considered the blank negligible (*see* Note 5, p. 435).

Effect of Iron—Some investigations were carried out on the effect of iron on the absorption characteristics of molybdenum blue and on the use of nitric acid as an alternative oxidizing agent. The new draft procedure, which involved a final dilution to a volume of 50 ml., was further modified, and the results obtained on the samples then showed more general agreement.

It was observed that the effect of omitting iron from the calibration solutions was very marked. The two main features were :

(i) An intense brown background colour was produced which gave rise to approximately twice the absorption value obtained in the presence of iron

(ii) The slope of the curve was steeper than when iron was present in the test solutions.

These results showed the necessity for the presence of iron in the calibration solutions.

Final Volume of Solution—Arising from the change in final volume to 50 ml. there were indications that the changed acid concentration had a detrimental effect, and a series of tests was carried out in order to clarify this point. 2·4 g. of a particular sample (MGS/19) were dissolved in 40 ml. of dilute sulphuric acid (1 : 9). The solution was then oxidized by the dropwise addition of nitric acid (sp. gr. 1·42), boiled, cooled, and finally diluted with water to 200 ml., using a standard flask. This solution was exactly equivalent to 0·60 g. of sample dissolved in 10 ml. of dilute sulphuric acid (1 : 9) in a final volume of 50 ml. From this stock solution, 10-ml. portions were accurately transferred to 10 pairs of clean 250-ml. beakers. Increasing quantities of dilute sulphuric acid (1 : 9) were then added to the pairs of beakers so that a range of from 0 to 4·5 ml. was covered in steps of 0·5 ml. This gave a range of acidity equivalent to 10–32·5 ml. of dilute sulphuric acid (1 : 9) for 0·60 g. of sample. The solutions were then treated exactly as described in the procedure (p. 436), one beaker of each pair being treated as the compensating solution. Ilford 606 filters and a 4-cm. cell were used with a 1·20 setting on the absorptiometer, and the results are given in Table V.

Conclusions

Results of these investigations showed that the suggested conditions, *i.e.*, 0·60 g. sample, 20 ml. of dilute sulphuric acid (1 : 9), in a final volume of 50 ml., were quite satisfactory ; using any greater volume of acid solvent prevented the full development of the silico-molybdate complex. It appeared also that at the lower acid concentration there was incomplete formation of silico-molybdate.

The use of nitric acid as an alternative oxidizing agent gave erratic results, although under similar conditions reproducible figures were obtained when permanganate was used. The results obtained on the effect of dilution, hot-plate temperature, and free acidity were considered in relation to the background colour of the solution, and it was decided to revert to the use of potassium permanganate, using hydrogen peroxide for reduction of the excess.

Table V

EFFECT OF SULPHURIC ACID CONCENTRATION

Sulphuric Acid (1 : 9), ml.	Equivalent of sulphuric acid (1 : 9) per 0·6 g. of sample, ml.	Test Solution Reading	Compensating Solution Reading	Difference
0	10·0	0·43	1·06	0·63
0·5	12·5	0·33	1·06	0·73
1·0	15·0	0·30	1·06	0·76
1·5	17·5	0·295	1·06	0·765
2·0	20·0	0·28	1·06	0·78
2·5	22·5	0·31	1·06	0·75
3·0	25·0	0·345	1·06	0·715
3·5	27·5	0·365	1·06	0·695
4·0	30·0	0·42	1·06	0·64
4·5	32·5	0·52	1·06	0·54

Table VI

RESULTS OBTAINED BY FINAL LOW-RANGE METHOD

Analyst	Sample MGS/18 Si, %	Sample MGS/19 Si, %	Sample MGS/52 Si, %
A	0·014	0·039	0·045
	0·013	0·039	0·046
	0·014	0·039	0·046
B	0·013	0·041	0·048
	0·014	0·041	0·048
	0·014	0·041	0·047
C	0·014	0·039	0·045
	0·014	0·040	0·045
	0·014	0·040	0·045
D	0·014	0·038	0·043
	0·013	0·038	0·045
	0·014	0·038	0·043
E	0·018	0·039	0·044
	0·017	0·039	0·044
	0·017	0·039	0·043
F	0·016	0·040	0·045
	0·014	0·040	0·046
	0·015	0·040	0·044
G	0·017	0·044	0·045
	0·016	0·043	0·044
	0·017	0·044	0·043
H	0·015	0·041	0·046
	0·015	0·041	0·047
	0·016	0·041	0·046
I	0·014	0·040	0·045
	0·013	0·039	0·044
	0·014	0·039	0·045
Average	0·015	0·040	0·045

All members of the Sub-Committee analysed circulated samples of each of three mild steels by this revised method, and obtained three figures for each sample. The results are given in Table VI.

These results were considered to be satisfactory, and Method II as given in Appendix II was submitted to the Main Committee.

References

1. "Silicon in All Types of Irons and Plain and Alloy Steels," B.S. 1121 : Part 10 : 1948.
2. E. J. VAUGHAN : "Further Advances in the Use of the Spekker Photoelectric Absorptiometer," (Monograph) pp. 6–7 : 1942, Institute of Chemistry.
3. F. W. HAYWARD and A. A. R. WOOD : "Metallurgical Analysis by Means of the Spekker Absorptiometer," p. 65 : 1944, Adam Hilger, London.
4. C. H. R. GENTRY and L. G. SHERRINGTON : *Journal of the Society of Chemical Industry*, 1946, vol. LXV, p. 90.

Appendix I

DETERMINATION OF SILICON IN PLAIN CARBON STEELS, LOW-ALLOY STEELS, AND CAST IRONS

DETAILS OF METHOD I

Introduction

Principle—The method consists of the oxidation of a solution of the steel in dilute sulphuric acid with permanganate, destruction of the excess, and dilution to a definite volume. The silicon is converted to silico-molybdate which is reduced to molybdenum blue, equivalent to the silicon present, by stannous chloride.

Range—0·05–2·0% Si.

Reproducibility—In the range 0·2–1·2% Si, ± 0·02% Si.

Application—The method does not include insoluble silica or silicates present in the sample. A standard gravimetric method is available for the determination of total silicon.[1]

Apparatus—A satisfactory apparatus for this method is the Hilger photo-electric absorptiometer. Using this instrument, suitable conditions for the determination of silicon are : Mercury vapour lamp ; Ilford yellow 606 filters together with H503 filters ; 0·5, 1, 2, or 4-cm. cells depending on the silicon content of sample. Other instruments of similar type may be used, for which modifications of operational detail will be required.

Reagent Solutions—The reagents required for the determination are :

Sulphuric acid (1 : 19)
Potassium permanganate (2%)
Ammonium molybdate (5%)
Sulphuric acid (sp. gr. 1·27)
Stannous chloride (1·2%)
Hydrogen peroxide (2 vols.)

Procedure

Add 70 ml. of sulphuric acid (1 : 19) to 0·5 g. of sample in a resistance glass beaker and simmer gently until dissolved. Oxidize with 2% potassium permanganate solution until a permanent precipitate of manganese dioxide is just obtained. Boil gently for 1 min. and then add hydrogen peroxide (2 vols.) dropwise, until the precipitate of manganese dioxide is just discharged.

Cool, dilute to 250 ml. in a graduated flask and mix thoroughly (Note 1, p. 435). Pipette two 20-ml. fractions into 100-ml. graduated flasks and treat as follows, maintaining the temperature of the solutions at 15–20° C. throughout :

Test Solution—Add 35 ml. of water followed by 10 ml. of 5% ammonium molybdate solution. Mix and stand for 3–5 min. Add 20 ml. of sulphuric acid (sp. gr. 1·27) and 10 ml. of 1·2% stannous chloride solution. Dilute to 100 ml., mix and allow to stand for 15 min. (Note 2).

Compensating solution—Add 35 ml. of water followed by 20 ml. of sulphuric acid (sp. gr. 1·27), 10 ml. of 5% ammonium molybdate solution, and 10 ml. of stannous chloride solution (1·2%). Dilute to 100 ml., mix, and allow to stand for 15 min. (Note 2).

Obtain the difference between the absorption reading of the test solution and that of the compensating solution, subtract the 'blank' obtained from the calibration tests, and convert to percentage silicon from a calibration curve prepared under similar conditions.

CALIBRATION

Introduction

Calibration curves are prepared most conveniently by the use of two silicate solutions of different strengths, obtained by the dilution of a primary silicate solution. Standard silicate solutions should not be stored but should be prepared freshly for each calibration series. A suitable form of pure silica for the preparation of standard solutions is Brazilian quartz. As a safeguard against extraneous errors during preparation of the solutions, it is recommended

that a gravimetric check[1] should be carried out on a suitable volume of the primary solution, *i.e.*, 100–200 ml.

Primary Silicate Solution—Weigh 0·8562 g. of finely ground (100 mesh) pure silica previously ignited at 1000° C. Fuse in a platinum dish with 5 g. of anhydrous sodium carbonate. Extract with 100 ml. of water in a nickel beaker, and filter through a paper-pulp pad, washing with 1% sodium carbonate solution. Collect the filtrate and washings in a 1000-ml. graduated flask, dilute to 1 litre and mix.

1 ml. of this solution contains 0·0004 g. of silicon.

Dilute Silicate Solution "A"—Dilute 100 ml. of the primary silicate solution to 1 litre and mix.

1 ml. of this solution contains 0·00004 g. of silicon.

Dilute Silicate Solution "B"—Dilute 20 ml. of the primary silicate solution to 1 litre and mix.

1 ml. of this solution contains 0·000008 g. of silicon.

Procedure

To 5 g. of ferrous sulphate crystals ($FeSO_4.7H_2O$) (Note 3) add 120 ml. of dilute sulphuric acid (1 : 19) and 20 ml. of water (Note 4), and simmer gently until dissolved. Treat with potassium permanganate and hydrogen peroxide solutions exactly as for the determination of silicon (*see* "Procedure," p. 434) and dilute to 500 ml. This gives the base solution.

Calibration Test Solution—Pipette a number of 20-ml. fractions from the foregoing base solution, and add varying amounts of the silicate solutions "*A*" and "*B*" to cover the range 0–2·0% silicon. Treat the solutions for colour development exactly as for the determination of silicon (*see* "Test Solution," p. 434), but reducing the specified 35 ml. of water added by an amount equal to the volume of the standard silicate solution used.

Compensating Solution—Pipette a further 20-ml. fraction from the base solution, and treat as described under "Compensating Solution" in the procedure for the determination of silicon.

For each of the cell sizes, 0·5, 1·0, 2·0, and 4·0 cm. obtain the difference between the absorption reading of the calibration test solution containing no added silicon and the compensating solution. This is the 'blank' on the calibration tests (Note 5).

Obtain the difference between the absorption readings for each coloured calibration test and the compensating solution on as many cell sizes as practicable and deduct from each of these values the 'blank' value obtained on the particular cell size.

For each cell size, plot the corrected differences against the amount of added standard silicate solution.

Calculation

Silicon contents may be read directly from the appropriate graph, and should be reported as a percentage, to two places of decimals.

NOTES

(1) In the case of grey cast irons, or steels containing tungsten or other elements giving insoluble products at this stage, decant sufficient of the solution through a dry filter paper (No. 40), to provide the subsequent fractions. The initial runnings must be discarded and the filtrate should be collected in a *dry* flask or beaker.

(2) The specified amounts of these reagents should be maintained within ± 0·5 ml. The use of automatic pipettes (or fast-running burettes) will be an advantage in making these additions.

(3) Ferrous sulphate is recommended for the base iron addition since it has been found to give less colour development due to silicon than any form of pure iron at present commercially available.

(4) These amounts of ferrous sulphate, sulphuric acid, and water reproduce similar conditions with respect to iron and sulphuric acid contents as exist in the solution of the steel sample.

(5) The blank obtained in the calibration determinations is due to any silicon in the ferrous sulphate, plus any silicon in the reagents, plus any other colour effects due to the reagents. Only the latter two effects are common to both steel samples and calibration tests; normally their net effect is exceedingly small and no correction need be made to the silicon determinations in steel. Nevertheless any increase in these factors, due to inferior reagents, would reflect in high silicon results on steel determinations. This possibility can be guarded against by carrying out a 'blank' test (*i.e.*, a calibration test containing no added silicon, with its corresponding compensating solution) with each batch of silicon determinations. The difference between these two solutions should equal that obtained in the previous calibration series. Should an increased blank be found its cause must be traced and the responsible reagents rejected.

Appendix II

DETERMINATION OF SMALL AMOUNTS OF SILICON IN PLAIN AND LOW-ALLOY STEELS AND IRONS

DETAILS OF METHOD II

Introduction

Principle—The sample is dissolved in dilute sulphuric acid and insoluble material is removed by filtration. Silicon is converted to silico-molybdate, which is reduced to molybdenum blue by oxalic acid and ferrous sulphate, and the resultant colour is measured photometrically.

Range—Up to 0·05% Si.

Reproducibility—With 0·01% Si present, ± 0·002% Si; with 0·05% Si present, ± 0·005% Si.

Application—The method does not include insoluble silica or silicates present in the sample. A standard gravimetric method is available for the determination of total silicon.[1]

Special Apparatus Required

A satisfactory apparatus for this method is the Hilger photo-electric absorptiometer. Using this instrument, suitable conditions for the determination of silicon are: Mercury vapour lamp; Ilford Yellow Filters No. 606, together with H503 filters; 4-cm. cells.

Other instruments may be used, for which modifications of operational details will be required.

Grade *A* graduated glassware shall be used throughout.

Reagents Required—All reagents shall be of guaranteed purity and distilled water shall be used throughout. Solutions shall be freshly prepared and, where

necessary, filtered. Details of the solutions required are as follows :

Sulphuric Acid (1 : 9)—To 800 ml. of water, add 100 ml. of sulphuric acid (sp. gr. 1·84), mix, cool, and dilute to 1 litre.

Potassium Permanganate (2%)—Dissolve 2 g. of potassium permanganate crystals in cold water, and dilute to 100 ml.

Hydrogen Peroxide (2 *vols.*)—Dilute 10 ml. of hydrogen peroxide (20 vols.) to 100 ml.

Ammonium Molybdate (10%)—Dissolve 10 g. of ammonium molybdate crystals ($(NH_4)_6Mo_7O_{24}.4H_2O$) in water, and dilute to 100 ml.

Ferrous Ammonium Sulphate (2%)—Dissolve 2 g. of ferrous ammonium sulphate crystals ($FeSO_4.(NH_4)_2SO_4.6H_2O$) in 50 ml. of water containing 1 ml. of dilute sulphuric acid (1 : 9) and dilute to 100 ml.

Oxalic Acid (10%)—Dissolve 10 g. of oxalic acid crystals ($(COOH)_2.2H_2O$) in 50 ml. of warm water, dilute to 100 ml., and cool.

Sampling

Recommended methods of obtaining a suitable sample for the analytical procedure outlined below will be the subject of a British Standard Specification, at present circulated as a draft for comment (CM(ISE)2437).

Procedure

Add 20 ml. of sulphuric acid (1 : 9) to 0·6 g. of sample in a resistance glass beaker and simmer until dissolved, avoiding loss by evaporation. Oxidize the hot solution with dropwise additions of 2% potassium permanganate solution until a permanent precipitate is obtained, add hydrogen peroxide (2 vols.) until the precipitate is just discharged, bring to the boil, and cool.

Dilute to 50 ml. in a graduated flask, and mix thoroughly (Note 1). Pipette two 10-ml. fractions into 50-ml. graduated flasks and treat as follows :

Test Solution—Add 10 ml. of 10% ammonium molybdate solution. Mix and allow to stand for 20 min. at 20 ± 2° C. Add 20 ml. of 10% oxalic acid solution, mix, and allow to stand for 5 min. Add 5 ml. of 2% ferrous ammonium sulphate solution, dilute to 50 ml., and mix thoroughly. Stand for 5 min.

Compensating Solution—Add 20 ml. of 10% oxalic acid solution, followed by 10 ml. of 10% ammonium molybdate solution, and 5 ml. of 2% ferrous ammonium sulphate solution, *mixing after each addition*. Dilute to 50 ml. and mix thoroughly. Stand for 5 min.

Obtain the difference reading between the absorption of the test solution and that of the compensating solution, using 4-cm. cells, and relate this to a calibration curve prepared under similar conditions, after deducting the ' blank ' on the calibration tests. (*See* below).

CALIBRATION

Solutions Required

A suitable form of pure silica for the preparation of standard solutions is Brazilian quartz. As a safeguard against extraneous errors during preparation of the solutions, it is recommended that a gravimetric check[1] should be carried out on a suitable volume of the primary solution, *i.e.*, 100–200 ml.

Primary Silicate Solution—Weigh 0·8562 g. of finely ground (100 mesh) pure silica previously ignited at 1000° C. Fuse in a platinum dish with 5 g. of anhydrous sodium carbonate. Extract with 100 ml. of water in a nickel beaker, and filter through a paper pulp pad, washing with 1% sodium carbonate solution. Collect the filtrate and washings in a 1000-ml. graduated flask, dilute to 1 litre and mix.

1 ml. of this solution contains 0·0004 g. of silicon.

Dilute Silicate Solution—Dilute 30 ml. of the primary silicate solution to 1 litre and mix.

1 ml. of this solution contains 0·000012 g. of silicon.

Standard silicate solutions should not be stored, but should be freshly prepared for each calibration series.

Procedure

To 15 g. of ferrous sulphate crystals ($FeSO_4.7H_2O$) (Note 2) add 70 ml. of sulphuric acid (1 : 9) and 25 ml. of water (Note 3). Simmer gently until dissolved. Treat with potassium permanganate and hydrogen peroxide solutions exactly as described under " Procedure " for the determination of silicon (this page), and dilute to 250 ml. This forms the base solution.

Calibration Test Solution—Pipette six 10-ml. fractions from the foregoing base solution and add varying amounts of the dilute silicate solution as follows :

Dilute Silicate Solution, ml.	Equivalent Silicon, %
0·0	Nil
1·0	0·01
2·0	0·02
3·0	0·03
4·0	0·04
5·0	0·05

Treat these solutions for colour development as described under " Test Solution " in the procedure for the determination of silicon (this page).

Compensating Solution—Pipette a further 10-ml. fraction from the base solution, and treat as described under " Compensating Solution " in the procedure for the determination of silicon.

Using 4-cm. cells, obtain the difference between the absorption reading of the calibration test solution with no added silicon and that of the compensating solution. This is the ' blank ' on the calibration tests (Note 4).

Again using 4-cm. cells obtain the difference between the absorption readings for each coloured calibration test solution and the compensating solution. Deduct from each of these values the ' blank ' value obtained above.

Plot the corrected differences against percentage of silicon derived from the amount of standard silicate solution added.

NOTES

(1) In the case of alloys containing elements giving insoluble products at this stage, decant sufficient of the solution through a filter paper (Whatman No. 40) to provide the subsequent fractions. The initial runnings must be discarded and the filtrate should be collected in a *dry* flask or beaker.

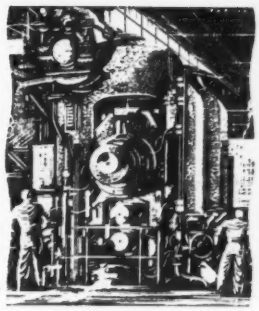
(2) *See* Note 3, p. 435.

(3) *See* Note 4, p. 435.

(4) *See* Note 5, p. 435.

IRON AND STEELWORKS ENGINEERING

THE IRON AND STEEL ENGINEERS GROUP



The Supply and Distribution of Water to Iron and Steel Works

By J. L. Daniel

SYNOPSIS

The paper deals with the supply and distribution of water at the Corby Works of Messrs. Stewarts and Lloyds, Ltd. Brief descriptions are given of the initial problems of water supplies from various sources, and of subsequent methods of distribution within the works, including supplies to tube works and a cold-strip mill.

To justify the building of an iron and steel works on any particular site, the first problem to be solved after sources of other raw materials have been proved is the finding of a plentiful supply of water, necessary for the production of the iron and steel.

Corby was chosen as a site because of its position on the ore fields of Northamptonshire. Unfortunately, subterranean water supplies in this district are very poor; the average yearly rainfall is only 25 in., compared with more than 50 in. in other parts of the country where iron and steel works exist. Corby is four miles from the Rutlandshire border, and stands 337 ft. above sea level. The surrounding lands are undulating, but are not suited to the harnessing of large quantities of water for continuous distribution. The Eye Brook reservoir, which provides the main supply, is 225 ft. above sea level; this means that there is no natural head of water at the works, all other sources of surface water being below the Corby level.

This paper describes the main sources of supply and pumping equipment, the distribution from a central station, and the water-treatment plant at the Corby works. Approximately half the inflow of water must be treated before distribution to sections where the use of soft water is essential. The problems of distribution are manifold since there are numerous points of application, often involving extremely complicated layouts of pipe-lines.

SOURCES OF SUPPLY

Before the integrated Iron and Steel Works were built in 1933, the old Corby Works, consisting of three small blast-furnaces only, obtained water supplies from a disused clay pit and from one or two wells in the vicinity. Even in those days water problems were often acute: the very low yield from these sources was only a fraction of the requirement for a large iron and steel works. Other sources were sought and eventually found, and now yield more than 4 million gallons per day. The main source of supply is the Eye Brook reservoir; the scheme for the construction of this entailed the seeking of powers to dam a tributary of the River Welland, called the Eye Brook. For this purpose a Bill was placed before Parliament, and it became law in 1931.

The new Corby Works were built before work could be commenced on the construction of the reservoir, so other sources had to be found. In 1932, water rights were obtained of two private lakes on the Willow Brook, a tributary of the River Nene. A pumping station was built at Blatherwycke with a 14-in. dia. pipe-line, 8 miles long, to the Corby Works. The yield from this source was about $2\frac{1}{2}$ million gallons per day; an additional pumping station on Abyssinian tube wells was put down at Duddington with a 3-mile pipe-line to Blatherwycke, where it joined the Blatherwycke line to Corby. The total length of the pipe-line to Corby was 11 miles, with a boosting station installed at Deene, half-way between Blatherwycke and Corby.

Further water rights were acquired from gravel pits at Thrapston; from these a supply of $2\frac{1}{2}$ million gallons per day was expected, with a constant level maintained in the pits by infiltration through the gravel. However, the inflow to the pits varied considerably with the seasons, and the yield was

Manuscript received 26th May, 1950.

Mr. Daniel is on the staff of Messrs. Stewarts and Lloyds, Ltd., Corby.

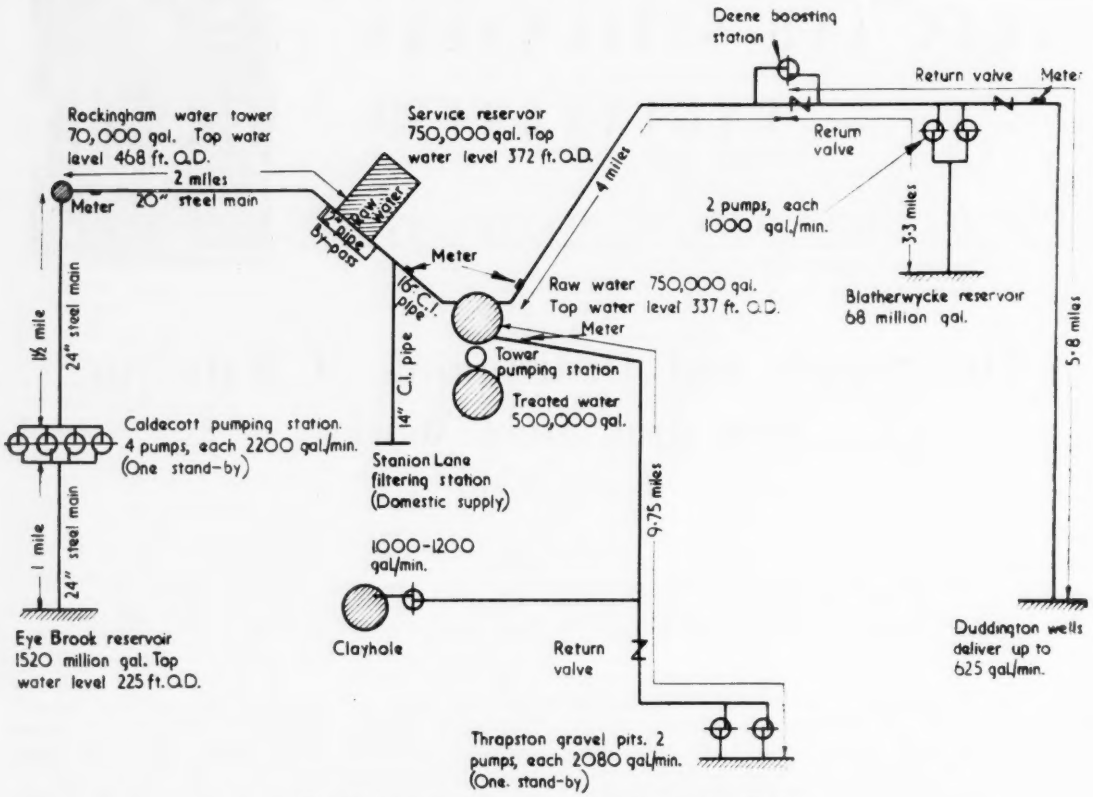

Deene boosting station
Return valve
Meter
Rockingham water tower 70,000 gal. Top water level 468 ft. O.D.
2 miles
20" steel main
Meter
Service reservoir 750,000 gal. Top water level 372 ft. O.D.
Raw water
12" pipe by-pass
4 miles
Return valve
2 pumps, each 1000 gal./min.
3·3 miles
Meter
16" C.I. pipe
Raw water 750,000 gal. Top water level 337 ft. O.D.
Blatherwycke reservoir 68 million gal.
1½ mile
24" steel main
14" C.I. pipe
Meter
Tower pumping station
Treated water 500,000 gal.
5·8 miles
Caldecott pumping station. 4 pumps, each 2200 gal./min. (One stand-by)
Stanion Lane filtering station (Domestic supply)
1 mile
24" steel main
9·75 miles
1000-1200 gal./min.
Eye Brook reservoir 1520 million gal. Top water level 225 ft. O.D.
Clayhole
Return valve
Duddington wells deliver up to 625 gal./min.
Thrapston gravel pits. 2 pumps, each 2080 gal./min. (One stand-by)

Fig. 1—Layout of water supplies for Corby Works

not maintained. It became apparent during the drought of 1933–34 that Blatherwycke, Thrapston, and Clay Pit supplies would be insufficient to meet the works demands, so it was decided to construct the Eye Brook reservoir which was planned to yield over 5 million gallons per day. Unfortunately, results have shown that $4\frac{1}{4}$ million gallons including compensation water is the highest daily figure obtainable. This reservoir, $5\frac{1}{2}$ miles from Corby, is one of the largest in the East Midlands, but is very shallow ; consequently the water has a high algae content which makes filtering and softening difficult.

Water from the Thrapston Gravel Pit still plays an important part in the total supply to the works. Considerable quantities are pumped from this source in the early months of the year, to conserve the supplies in the Eye Brook reservoir before the commencement of the summer season.

The natural surface waters of the East Midlands have a total hardness of about 20°, of which 10° is temporary hardness. Those in the districts of Eye Brook, Blatherwycke, and Thrapston vary in hardness, and must be treated at the works central distribution station. The Blatherwycke source is augmented by the overflow from the works and therefore has other chemicals in solution which must be removed for boiler-feed purposes. The solids in suspension precipitate to a great extent during the 8-mile flow back to Blatherwycke.

The diagrammatic arrangement of the present sources of supply is shown in Fig. 1.

Eye Brook Reservoir

The reservoir is situated in the County of Rutland near the Northamptonshire border. The catchment area is 15,000 acres, and the lake area is 375 acres at top water level ; the reservoir has an average depth of water of 15 ft. and a maximum capacity of 1520 million gallons at a level of 225 ft. O.D.

The dam is an earth embankment with a puddled clay core ; its length is 1700 ft., and the maximum height is 45 ft.

The water in the outgoing 24-in. dia. steel main flows for one mile to the Caldecott pumping station, at 173 ft. O.D. The station consists of four centrifugal pumps, each capable of delivering 2200 gal./min. against a head of 300 ft. In practice, two pumps deliver 4100 gal./min., and three pumps 5700 gal./min. ; the fourth pump is a stand-by. A Diesel generator is provided to supply current in the event of power failure. Each pump is driven by a 250-b.h.p. squirrel cage motor from a 400-volt, 3-phase, 50-cycle supply. The pumps deliver into a 24-in. dia. steel main extending $1\frac{1}{2}$ miles to the Rockingham water tower. This tower is 60 ft. above ground level, and holds 70,000 gallons when the top water level is 468 ft. O.D. The Caldecott pumps are electrically controlled from the water tower, starting and stopping automatically at pre-determined levels in the tower.

Delivery from the tower gravitates through a 20-in. dia. steel main, 2 miles long, to the works service reservoir. This is 150 ft. long × 75 ft. wide × 11 ft. deep, and contains 750,000 gallons. The top level at 372 ft. O.D. is controlled by two ball-valves in series.

Thrapston Gravel Pits

These pits lie near the River Nene, about 10 miles south-east of Corby. They have been formed by the excavation of gravel, which has been taking place for many years.

A pumping station is situated nearby, at 90 ft. O.D., which consists of two centrifugal pumps, each capable of delivering 2080 gal./min. against a head of 410 ft. ; they are driven by 350-b.h.p. motors, and pump into an 18-in. dia. pipe-line to Corby. The pumps are remotely controlled from the Corby central distributing station.

Blatherwycke Lakes and Duddington Wells

The Blatherwycke reservoir, which was constructed as an ornamental lake about a hundred years ago, provided the Corby Works with water in the initial stages of production. It has a capacity of 68 million gallons when the top level is 164 ft. O.D. The pumping station contains two centrifugal pumps, each capable of delivering 1000 gal./min. against a head of 290 ft., driven by 125-b.h.p. motors ; these are remotely controlled from the central distributing station at Corby.

The Abyssinian tube wells at Duddington consist of two batteries of 18 wells, sunk near the banks of the River Welland. Each battery has a common 9-in. dia. suction pipe to the pump house at 110 ft. O.D. Three special low-lift self-priming pumps with air extractors, each capable of 625 gal./min. against 30 ft. head and driven by 12-b.h.p. motors, deliver water from the 9-in. dia. suction pipes ; and three high-lift pumps, each capable of 625 gal./min. against 400 ft. head, driven by 120-b.h.p. motors, deliver into the 18-in. dia. main to Blatherwycke. A yield of one million gallons per day has been obtained from these wells. The Deene boosting station on the Blatherwycke line, at 242 ft. O.D., contains two

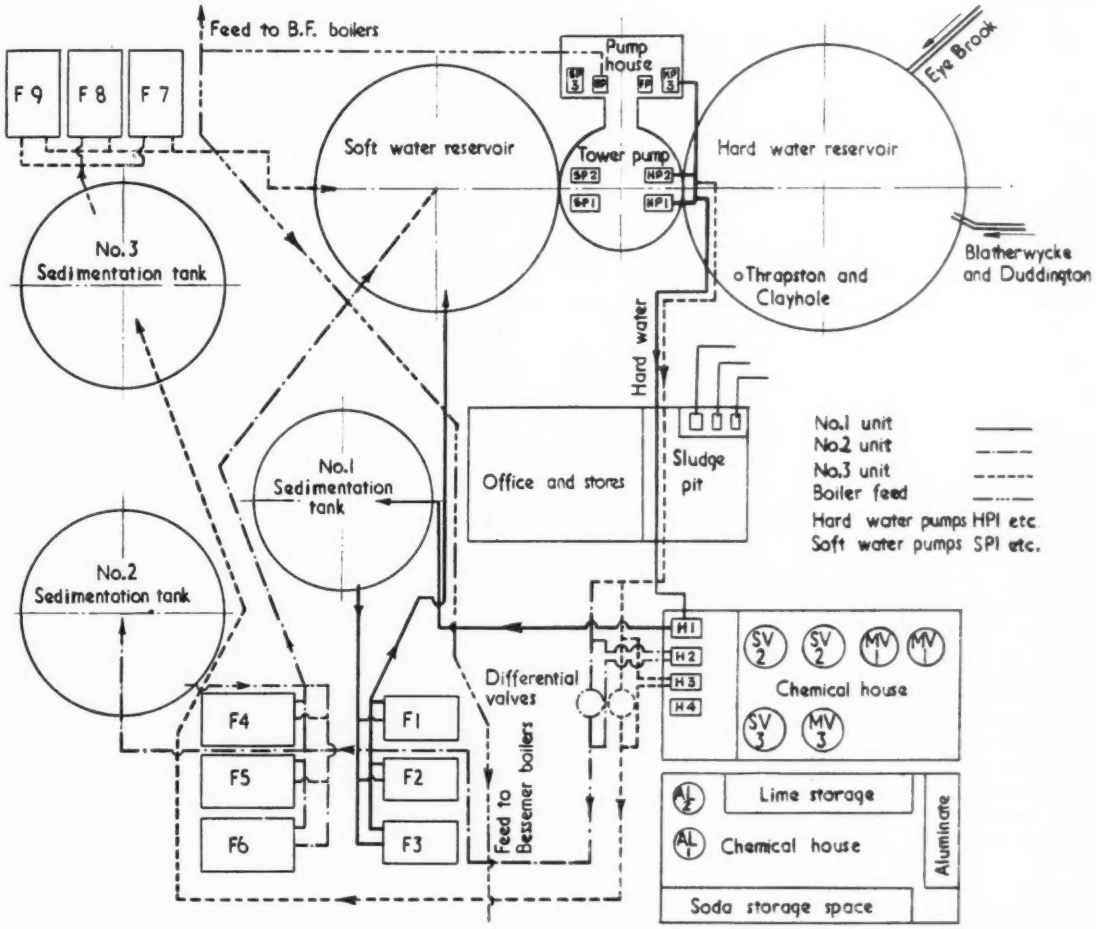


Fig. 2—Layout of water-treatment plant

centrifugal pumps, each capable of 2290 gal./min. against 280 ft. head, driven by 265-b.h.p. motors.

Since the completion of the Eye Brook Reservoir in 1940, Blatherwycke, Duddington, and Clay Pit have been only secondary sources of supply.

CENTRAL DISTRIBUTING STATION

The station is situated approximately equidistant from the blast-furnaces and rolling mills, and adjacent to the steel-making plant.

Figure 2 shows the diagrammatic layout of the station, which consists of :

Hard-water reservoir : 750,000 gal. capacity
Soft-water reservoir : 500,000 gal. capacity

3 Hard-water pumps : 3500 gal./min. capacity } against 120 ft. head
3 Soft-water pumps : 2500 gal./min. capacity }

3 Water-treatments units, together with pump house and necessary chemical-mixing and storage houses
Water tower 85 ft. high, with hard- and soft-water compartments, each compartment of 50,000 gal. capacity.

The hard-water reservoir receives raw water from the sources Eye Brook, Blatherwycke and Duddington, Thrapston, and Clay Pit.

The hard-water pumps (HP.1, HP.2, and HP.3) deliver into a header main, from which one pipeline feeds No. 1 water-treatment unit and another line feeds No. 2 and No. 3 units, as shown on the flow diagram, Fig. 2. The softened water is delivered from all three units to the soft-water reservoir, from which the soft-water pumps (SP.1, SP.2, and SP.3) deliver water to the blast-furnaces, coke ovens, Bessemer plant, mills, etc.

The discharge pipe-lines from all the soft- and hard-water pumps are directly connected to the soft- and hard-water compartments of the water tower. This ensures that the pumps always work against the 'head' of the tower, so that, in the event of an unavoidable stoppage of the pumps, the tower would be capable of providing a supply of water to all parts of the plant for some hours.

The system of water softening, for all three units, is by the 'lime and soda' process, the reagents employed being lime, soda ash, and sodium aluminate. The aluminate is dissolved into solution in No. 1 and No. 2 aluminate mixing vessels (AL.1, AL.2). The lime and soda are dissolved into solution in Nos. 1, 2, and 3 mixing vessels (MV.1, MV.2, and MV.3) and are then mixed with the dissolved aluminate. The complete softening solution is then pumped into storage vessels (SV.1, SV.2, and SV.3), each of which holds about eight hours' supply of solution for its appropriate water-treatment unit. The softening solution is pumped to the top of the sedimentation tanks through Nos. 1, 2, and 3 hydrostats (H.1, H.2, and H.3). The hydrostat pumps are operated by the pressure of the incoming raw water, thus ensuring that the amount of softening solution is adjusted to the quantity of water to be treated. In addition, the stroke of the hydrostat pumps can be adjusted so that any desired proportion of softening solution can be added to the hard water.

From the hydrostat the raw water is fed into the top of the sedimentation tanks, where the softening solution is mixed with the raw water. This passes down the mixer tube in the centre of the tanks, being thoroughly mixed by means of a water-operated agitator, then passes upwards at a slow rate to the top of the tanks, where the water is uniformly collected over the whole area ; the treated water remains in the sedimentation tanks for approximately 7–8 hours. The precipitated hardening salts fall to the bottom of the tanks, and are removed in the form of sludge. The softened water collected at the top of the tanks is delivered to the sand and gravel pressure filters (F.1, F.2, F.3, etc.), of which three are attached to each water-treatment unit. These filters mechanically clean the water and remove any suspended matter which may be present. From No. 2 and No. 3 units the soft water from the filters flows into the soft-water reservoir, and from No. 1 unit the soft water flows, usually, to the suction of the boiler-feed pump.

After treatment the hardness is reduced to 1·2°, with a total alkalinity of 3·7.

Distribution of hard untreated water to various plants is carried out by overhead and underground pipes : 8-in. dia. overhead and 6-in. dia. underground mains serve the blast-furnaces and coke-oven plants. The original main to the steelworks is now inadequate, and two additional temporary 4-in. dia. mains have been installed for the 40-in. blooming mill and open-hearth plants.

Soft water is distributed through 10-in. dia. and 6-in. dia. mains to the blast-furnaces and coke ovens, engineering shops, and miscellaneous services. Because of extensions, the original 8-in. dia. steelworks main is, again, no longer of sufficient capacity. A further 6-in. dia. main has been added to supply a new open-hearth plant.

Five local distributing stations are served from the central station. These are situated at the coke ovens, blast-furnace and open-hearth plants, the main group of rolling mills, and an isolated hot-strip mill. In addition, supplies are taken to the tube works, cold-strip mills, and basic-slag plant.

The quantities of hard and soft water distributed daily (every 24 hours) to the various sections of the plant are approximately :

	Hard Water, gal. × 10^3	Soft Water, gal. × 10^3
Blast-furnaces	251	540
Gas-cleaning plant	...	460
Sinter plants	...	165
Blast-furnace boilers	...	75
Coke ovens	467	105
Bessemer plant	14	301
Bessemer boilers	...	230
Rolling mills	480	75
Open-hearth plant	1	32
Tube works	447	65
Cold narrow strip mills	70	70
Mines department	...	25
Miscellaneous services	50	...

COKE OVENS AND BY-PRODUCT PLANT

An integrated iron and steel works is dependent, to a very large extent, on the supply of coke-oven gas. It follows, therefore, that adequate supplies of cooling water are essential, both for the efficient recovery of by-products and for the reduction of volume of gas for distribution to all sections of the works

Water requirements on the oven batteries are con-

fined mainly to the quenching of coke This is carried out by running the railroad coke car under a quenching tower, which is equipped with overhead spray pipes so arranged that the water is distributed over the red-hot coke ; the products of evaporation rise to atmosphere through the top of the tower, and the hot water gravitates or is pumped to the settling tanks for re-circulation.

In the Corby plant, coke is quenched by spent ammoniacal liquor, because of the difficulty of disposing of effluent without contaminating the brooks and pasture-lands in the district. The circulation of quenching liquor is similar to that of water, but, because of its highly corrosive nature, particular attention must be paid to the design of pumping equipment to withstand wastage. The vapour given off from the top of the quenching tower descends and settles over a considerable area, and all unprotected steelwork in the vicinity is subject to rapid deterioration. Painting costs in the neighbourhood, therefore, are high.

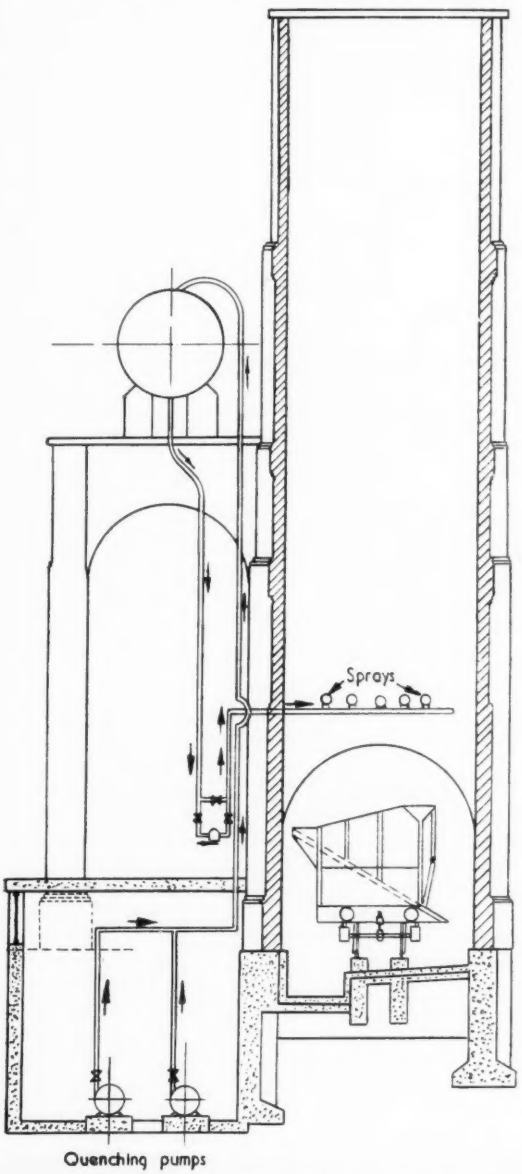


Fig. 3—Section through coke-oven quenching station

There are two identical quenching stations, situated at each end of the batteries comprising 124 ovens. Liquor is pumped from the by-product plant through a 6-in. dia. pipe to the pump suction chamber of the quenching station.

The brick tower is 53 ft. long and 80 ft. high ; a section through the tower and pump room is shown in Fig. 3.

The settling tanks are placed adjacent to the pump suction tanks, and are below coke-car rail level. Because of site conditions the size of the settling tank was restricted ; consequently the removal of accumulated coke breeze is almost a continuous operation. The pump suction tank is divided into two compartments, and the partition wall between the suction and the settling tank is provided with cross channels and openings equipped with timber gates, which allow either compartment of the suction tank to be isolated.

The pump room, also located below coke-car rail level, contains two specially designed centrifugal pumps, each capable of a delivery of 1000 gal./min. of hot and dirty liquor against a head of 85 ft., and driven by 55-b.h.p. motors. One pump performs the normal duty, and the other is a stand-by : both are connected to a 10-in. dia. delivery main supplying the overhead storage tank, which has a capacity of 10,000 gallons. The level of the fluid in the tank is automatically controlled by a float valve electrically connected to the pump motors. For make-up purposes and emergencies, the tank can be fed by a 4-in. dia. clean-water line taken from the works hard-water system. A 16-in. dia. feed-line is taken from the bottom of the storage tank to the quenching sprays inside the tower. Control is carried out by the locomotive driver, who operates a pilot valve hydraulically connected to a quick-acting valve in the 16-in. feed-line. Consumption is approximately 5000 gallons per 10-ton charge of coke quenched ; evaporation and other losses amount to about 55% of the total quantity of liquor sprayed.

All water requirements for other services are supplied by a 3-in. dia. clean-water pipe.

The distribution of water to by-product plants presents difficulties not encountered in other sections of iron and steel plants. Layout of piping becomes complicated, because of the many points of application, and at certain units, where failure of water would be critical, alternative supplies must be provided. Furthermore, conditions may alter with the changing coking rate, and the changing atmospheric temperature at different times of the year. It is therefore essential that there should always be ample supplies of water available for the by-product plant, even though maximum demands may cause embarrassment in other sections of the works. The layout of soft-water mains is shown in Fig. 4.

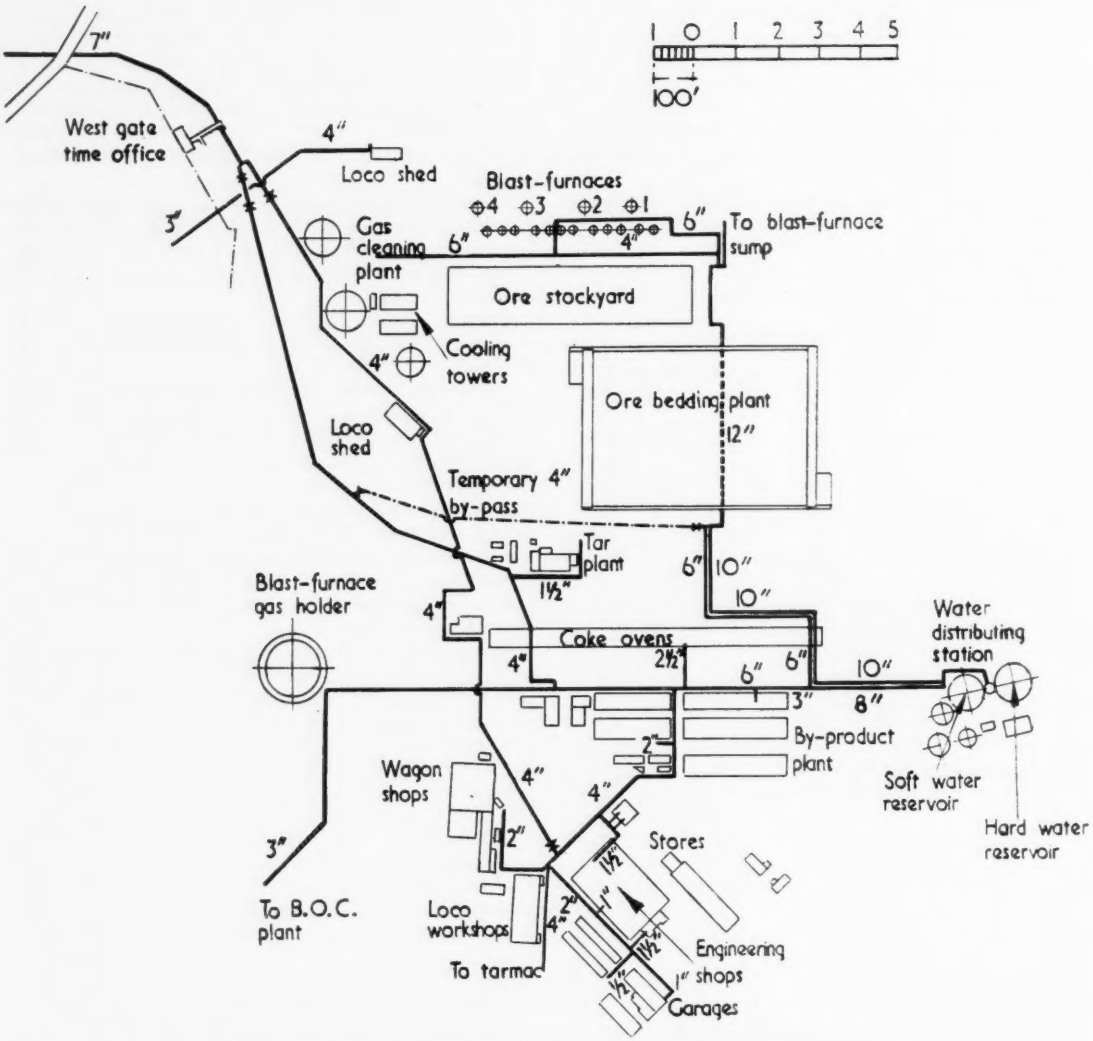


Fig. 4—Layout of treated-water mains, blast-furnaces, and coke ovens

Under normal conditions the plant is served by its own water system, consisting of circulating pumps and cooling towers ; water consumption is measured in terms of evaporation losses from the water coolers. For higher efficiency of tar, ammonia, and benzole recovery, lower gas temperatures are required, and it becomes necessary to supply fresh cold water to those units of plant where cold water is most desirable ; consequently, surplus water must be bled off into the clean-water drains.

The layout of the local distributing station and pipework is shown in Fig. 5. The main circulating pump delivers 30,000 gal./hr. against a head of 85 ft., discharging into two pipes, 12-in. and 16-in. dia., extending the full length of the plant. These two mains feed all the units operated on a closed circuit. The return mains are 16-in. and 9-in. dia., and these are connected at cooling tower *B*. From this point sluice valves regulate the flow to both cooling towers ; regulation is governed by temperatures taken periodically at both towers. Owing to site conditions, cooling tower *A* was located some distance from the plant ; the return main is increased to 12 in. dia. The tower is sufficiently elevated to allow the cooled water to gravitate through a 20-in. dia. pipe to the pump suction tank.

In the by-product units, where circuits are broken for external surface cooling, return water gravitates through channels to a hot well and suction tank, from which it is pumped at the rate of 5000 gal./hr. to cooling tower *B* ; towers *A* and *B* are capable of dealing with 22,000 and 44,000 gal./hr. respectively.

It will be seen from Fig. 5 that no by-product circulating water is returned to the works central station : return water from the plant would cause an

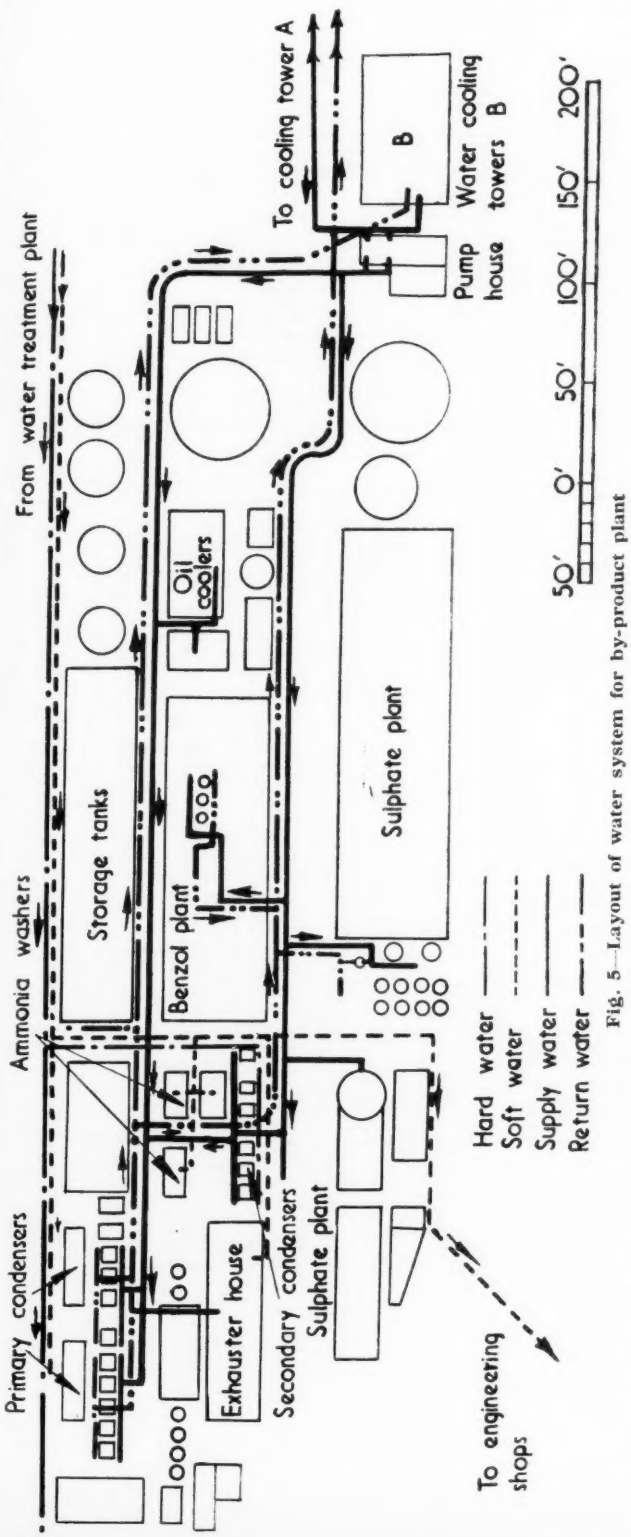


Fig. 5—Layout of water system for by-product plant

undesirable temperature rise of the water in the central station reservoir.

BLAST-FURNACE PLANT

Water used in the blast-furnace department may be divided into the following main sections :

Section 1—Cooling water for furnace lining
2—Washing water for gas-cleaning plant
3—Cooling water for turbo-blower condensers
4—Boiler feed-water
5—Cooling water for hot sinter
6—Miscellaneous purposes, such as dust-conditioning, spraying, and washing down.

Treated water should be used for sections 1–3 and should be re-circulated ; the water for sections 1 and 3 is returned to a common sump, which greatly increases the amount of water in circulation. Make-up water for the gas plant (approx. 500,000 gal./day) is also withdrawn from the same sump, and the replacement of this amount, together with that necessary to cover evaporation losses in furnace cooling and condenser circulating water (approx. 200,000 gal./day), provides substantial additional cooling of the circulating water.

A 12-in. dia. main carries the treated water from the central water station through a service tunnel under the ore-bedding plant to the pump-house sump at the blast-furnace plant. This tunnel also carries an extra 4-in. dia. soft-water main from the central water station to the blast-furnace boiler house, for boiler-feed make-up.

Section 1—Cooling Water for the Furnace Lining

Water Supply—There is a two-pressure system for (*a*) coolers below the mantel, (*b*) stack coolers. A flow diagram for the furnace water system is shown in Fig. 6.

Service (*a*) is provided by four pumps, two steam-driven and two electrically driven, each rated at 6000 gal./min. against a 75-ft. head. A 21-in. dia. pipe from the pump house feeds 10-in. dia. ring mains on Nos. 1–3 furnaces, while a separate 15-in. dia. main serves the 10-in. dia. ring main on No. 4 furnace, with an additional connection to No. 3 furnace ring main.

An extension of the 21-in. dia. main continues to the gas plant, and a further branch serves No. 1 and No. 2 sinter plants.

Service (*b*), for the coolers above the furnace mantels, is provided by four pumps, one steam-driven and three electrically driven, each rated at 1500 gal./min. against 140 ft. head. A 10-in. dia. line from the pump house feeds 6-in. dia. ring mains on Nos. 1–3 furnaces, and a separate 8-in. dia. line feeds a 6-in. dia. ring main on No. 4 furnace. This 8-in. line also has a connection to the No. 3 furnace 6-in. dia. ring main. The

Corby furnaces are provided with an exceptionally large amount of cooling above the stack, there being a total of 374 copper coolers on each furnace above the mantel; the highest ring is 77 ft. above the pump-house sump level.

Return Water from Furnaces—The return water from all the furnace coolers is led into a water trough which surrounds the furnace at about the level of the hot-blast ring main. All the individual pipes feeding into this trough are marked and are easily visible from the furnace platform, so that the operator can observe how the coolers are functioning. From this trough two discharge mains, situated at opposite sides of the trough, discharge into an underground return main. One 24-in. dia. return main is provided for Nos. 1–3 furnaces, which returns the water to a hot-water sump under the pump house. From there it is pumped by two centrifugal pumps, delivering 6000 gal./min. against 40 ft. head, to No. 1 and No. 2 cooling towers, and is returned to the common sump. Water from No. 4 furnace is returned in an underground 18-in. dia. main to sprays in two open cooling ponds, from which the cooled water is returned to the common sump.

Previously, return water from below the mantels was collected in annular troughs around the bases of the furnaces ; but after a break-out in which a trough and branches to the underground main were filled with slag and iron, this system was discarded in favour of that now in use.

A method more suitable than returning water by underground mains to the sump would no doubt be by an overhead pipe, or open launder, if headroom and plant layout would permit.

Water Storage—Adequate storage for use in the event of supply failure is essential if a blast-furnace plant is to maintain full output continuously.

A reinforced concrete tank of 120,000 gallons capacity, with water level approximately 85 ft. above pump-house sump level, forms a pressure reserve on the 21-in. dia. main to the furnace coolers below mantel level. Also, two storage tanks at ground level, of total capacity 80,000 gallons, are kept full for use in emergency.

Since over 800,000 gallons of make-up water per day are required for furnaces and gas plants, the total storage does not allow protracted running of the plant at normal load in the event of failure of supply.

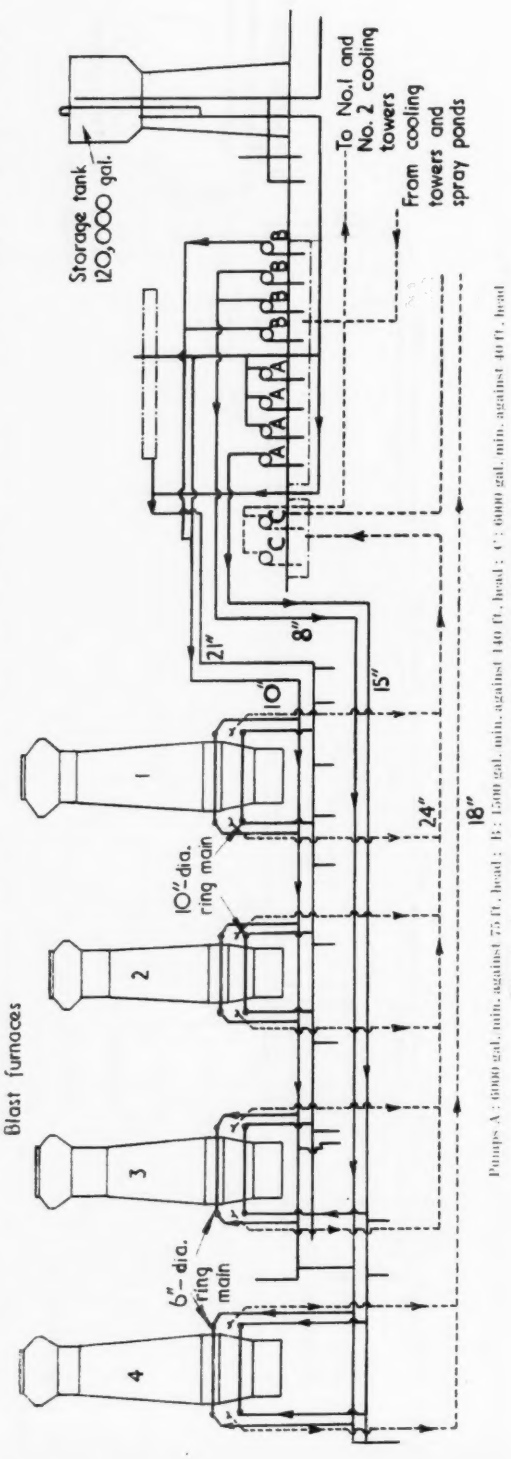
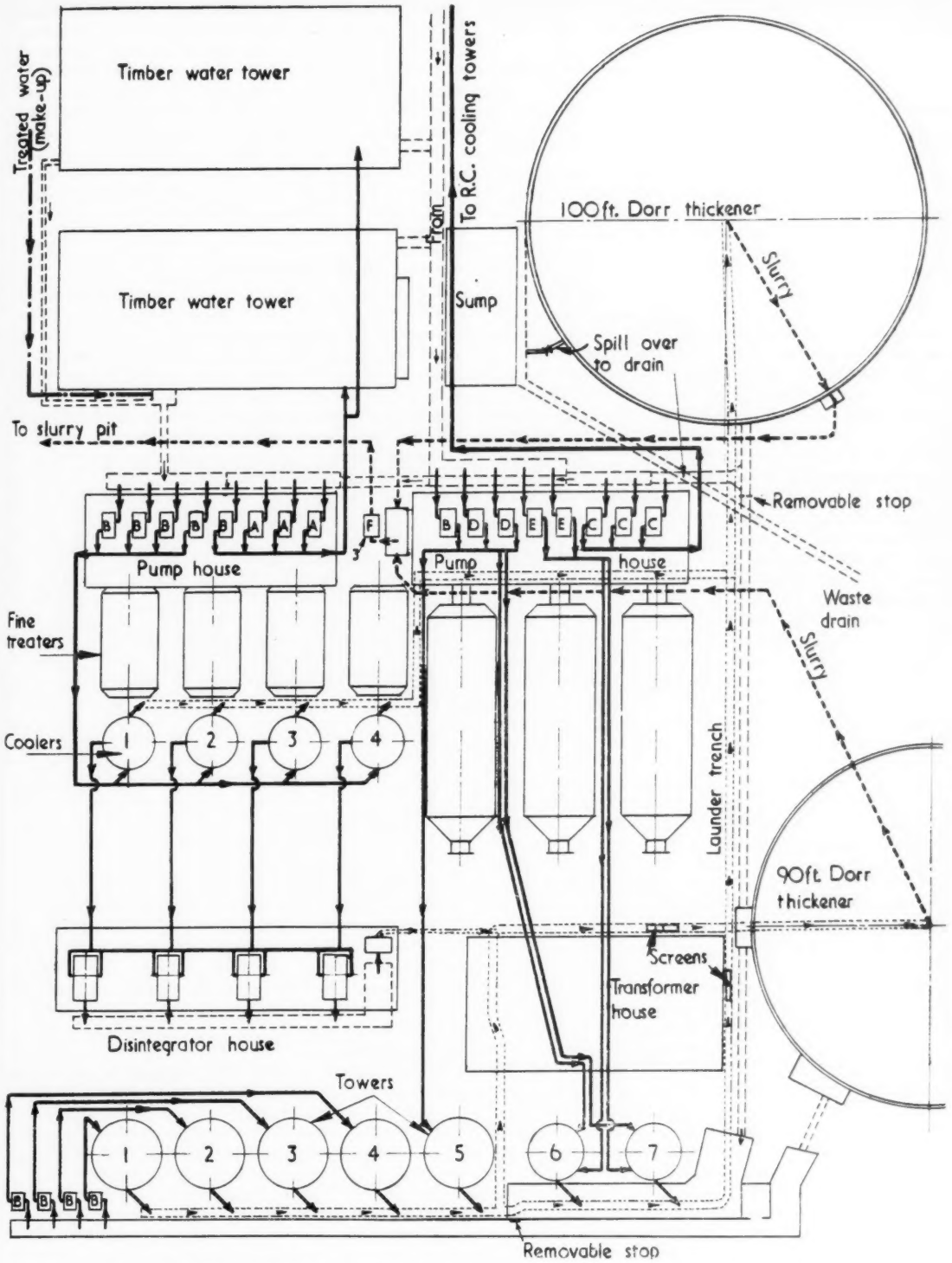


Fig. 6—Layout of water system for blast-furnace plant

Section 2—Washing Water for the Gas-Cleaning Plant

Most blast-furnace plants use large amounts of water for gas cleaning in washing towers, disintegrators, and/or wet electrostatic fine-treaters. The three processes are used in series, commencing with washing towers. A flow diagram for the gas-cleaning plant is shown in Fig. 7.

Since the gas-cleaning plant is in a state of transition, there is a number of separate water re-circulating circuits, but in general all the water is cleaned, cooled, and re-circulated. However, to avoid too much induced hardness in this water, about 500,000 gal./day are allowed to 'spill over' to the drain, and an equivalent amount of treated water from the blast-furnace pump-house common sump is fed into the pump-house cold-water sumps to replace it.



Pumps A : 1000 gal. min. against 100 ft. head ; B : 1500 gal. min. against 140 ft. head ; C : 1500 gal. min. against 130 ft. head ;
D : 2000 gal. min. against 150 ft. head ; E : 200 gal. min. against 500 ft. head ; F : 350 gal. min. against 106 ft. head.

Fig. 7—Layout of water system for gas-cleaning plant

There are seven gas-washing towers, four of which are served with water from one pump house and three from another. The return water from towers Nos. 1–4 gravitates to a 90-ft. Dorr thickener, and thence along open channels to the pump-house sump for re-circulation. That from towers Nos. 5–7 gravitates to a 100-ft. Dorr thickener and from there to a hot-water sump, from which it is pumped through a cooling tower before being re-circulated. Each washing tower is served by a separate pump and 12-in. dia. pipe-line; this facilitates cleaning of the pipes when a tower is out of service. Discharge of water from the tower bottoms into the mild-steel launders, which are situated above platform level, is visible to the operator, who can thus easily locate any tower with a choked outlet. Two perforated screen plates in series, easily removable for cleaning, are placed in the discharge launders before each of the Dorr thickeners.

Electric pumps rated at 1500 gal./min. against 140 ft. head are used for towers Nos. 1–5, and pumps giving 2000 gal./min. against 150 ft. head for towers No. 6 and No. 7. These two towers have, in addition, an auxiliary high-pressure water-spray system serviced by an electric pump, giving 200 gal./min. against 500 ft. head, which draws off the treated-water main.

Gas from washing towers Nos. 1–4 passes through disintegrators and water-sprayed gas coolers before final cleaning in the electrostatic fine-treaters. Four electric pumps, rated at 1500 gal./min. against 140 ft. head, connected to a common header main, feed the disintegrator and cooling-tower sprays, and the water is returned to the hot-water sump through the 100-ft. Dorr thickener. The hot water is circulated through two cooling towers by three electric pumps capable of 1000 gal./min. against 100 ft. head. A small amount of water is also used for washing out the fine-treaters. All three water-cooling towers are rated at 180,000 gal./hr.

Sludge from the Dorr thickeners and fine-treater sumps is first pumped to a common sump and then by 4-in. and 5-in. suction unchokeable pumps to a disused ironstone pit more than one mile away. Experience has shown that, to obtain reasonable service from the slurry pipes before cleaning, the velocity of the slurry must be kept high, and a 4-in. bore pipe is the largest which can be used. All water gravitating from washing towers, thickeners, or cooling towers, is contained in open mild-steel launders or concrete channels which can be easily dredged, since the pipes may become blocked owing to the high concentration of solids in the water.

Section 3—Cooling Water for Turbo-Blower Condensers

There are four turbo-blowers in constant use, two with capacities of 42,500–50,000 cu. ft./min. of free air at 25 lb./sq. in. gauge, and two with capacities of 51,000–55,000 cu. ft./min. of air at a similar pressure. Steam pressure for all blowers is 350 lb./sq. in. at 600° F., and vacuum at exhaust is 28 in. of mercury.

The supply of water for condensers presents no special distribution problems, and the re-circulation through cooling towers follows normal power-station practice. All the machines are equipped with surface-type condensers, those for the smaller machines being capable of dealing with 32,200 lb./hr. of exhaust steam (3450 sq. ft. cooling surface), and those for the larger with 34,000 lb./hr. The various circulating-water pumps are rated from 4000 gal./min. against 45 ft. head to 8360 gal./min. against 58 ft. head; the water is cooled from 140° F. to 70° F. in six timber cooling towers, each of 180,000 gal./hr. capacity.

In addition to the above machines, there is a smaller stand-by turbo-blower and a 2500-kW. turbo-alternator equipped with a surface-type condenser of 2500 sq. ft., requiring 2790 gallons of water per minute.

Section 4—Boiler Feed-Water

The amount of water required for this purpose is small compared with the water requirements for those sections of a blast-furnace plant which have already been considered. Nevertheless the service is a vital one, and interruption of supply, leading to shortage of steam for turbo-blowers, may cause as much interference with normal plant operation as will failure of the larger services. For this reason it is advisable to have alternative sources of supply.

The blast-furnace boiler plant consists of five water-tube boilers, each rated at 42,000 lb./hr. of steam at 365 lb./sq. in. (gauge) pressure and 650° F. superheated steam temperature. Since most of the steam is used in the turbo-blowers and returned as condensate to the hot well, only a small quantity of make-up water, approx. 75,000 gal./day, is required. This is supplied through a 4-in. dia. main from the water-treatment plant at the Steelworks; an alternative supply is available from the 12-in. dia. treated-water main to the blast-furnace common sump. The make-up passes through a settling tank and pressure filters before delivery to a mixing tank, which also receives condensate from all the turbo-blowers, etc. From this point the whole boiler feed passes through surge tanks and de-aerators to the boiler-feed pumps. These consist of two electric pumps rated at 450 and 407 gal./min. respectively against 1060 ft. head, and two steam turbo-pumps of 300 and 140 gal./min. capacity with similar head.

At one time a special sedimentation tank and filters at the water-treatment plant were reserved exclusively for supplying boiler-feed make-up to the blast-furnace and Bessemer boilers. This system, which enabled specially treated water to be used for this service, was discontinued during the war and has not, as yet, been re-instituted.

Section 5—Sinter Plant Requirements

Water, delivered through sprays, is required for (*a*) conditioning the raw mix, (*b*) cooling hot sinter on the strand in the Dwight-Lloyd process, (*c*) protecting belts conveying return fines, and (*d*) in many instances for cooling the hot sinter before transference to the blast-furnace bins. Also, in the No. 3 sinter plant a supply of treated water is required for the oil coolers, used in conjunction with the hydraulic coupling on the main fan. This water then circulates through the ignition hood and is discharged into the tank connected to the hot-sinter spray-cooling circuit.

A considerable quantity of water is required for cooling sinter after discharge from the machine.

No. 3 sinter plant has a 60 ton/hr. output of sinter, which is discharged from the pallets into a mild-steel chamber fitted with water sprays and a short chimney. After cooling in this chamber the sinter is discharged into bottom-hoppered wagons, for transfer to the furnace bins. The surplus water from the cooling chamber was allowed at first to flow into the works drainage system. However, so much trouble was encountered from pipes becoming silted up with sinter fines that it was eventually decided to install a settling tank and re-circulating pump. This reinforced concrete tank is 29 ft. long, 14½ ft. wide, and 9½ ft. deep, and is divided into two sections to facilitate cleaning out while the plant is working. The circulating pump is rated at 200 gal./min. against 90 ft. head.

Sinter from the No. 1 and No. 2 sinter plants is discharged from the machines directly into skip hoists, and thence transported to the furnace bins in a dry condition. To avoid a dust problem when discharging into the scale cars, these bins are equipped with sprays served with hard water.

Section 6—Miscellaneous Water Requirements

This category includes spray water for blast-furnace dust conditioning at the furnace dustcatchers and the vortex gas-cleaning plant; hoses for the furnace operators for cooling iron and slag runners, etc.; and cooling water for air compressors, pump and fan bearings, and hot-blast stove valves.

Hard water can be used for dust-conditioning sprays, sinter-bin sprays, and hoses, and for these purposes a 6-in. dia. hard-water main is provided from the central water station to the blast-furnace plant.

A high-pressure water supply, boosted to 100 lb./sq. in., is incorporated in the furnace cooling-water system. By means of a 3-in. pump located near the furnaces and drawing from the service main, high-pressure water is available at 2-in. dia. ring mains on each furnace, for periodic washing through of coolers. Connections are also made to the furnace tops for washing down, and to water-cooled hot-blast stove valves and fire hydrants. An inhibited hydrochloric acid solution is pumped periodically through the furnace coolers and turbine condenser tubes, to remove sludge.

STEEL-MAKING PLANT

In small iron and steel plants where the layout is compact, most sections of the plant can be served from a central distributing station. In hilly districts, where there is an ample supply of water available at natural heads, one would not expect a sudden loss of flow water in cooling systems of furnaces; troubles are often encountered, however, owing to strainers becoming choked with leaves or weeds. In some installations it is necessary to provide large-capacity screens to deal with the incoming water.

In large plants situated in a flat district, each section of the plant has its own self-contained station, served with make-up water from the central station. In these layouts, the only long pipe-lines necessary are those for make-up purposes; usually, they are laid out as ring mains serving the various distribution centres. Another advantage of the sub-station principle is that equipment can be kept under close control. The comparatively small pumping units are usually duplicated, and pipe-work and valves are so arranged that quick change-over can be made in the event of failure.

Of the three high-output processes of steelmaking, namely, open-hearth, Bessemer, and electric arc, the open-hearth plant with modern furnaces is the most dependent on water cooling. Bessemer converters have no cooling system, and the only water requirements, other than for hydraulic operation of the converter tilting gear, are for steam raising and various services in the plant. In comparison with open-hearth furnaces, modern arc furnaces at Corby require half the quantity of water in terms of gallons of water per ton of steel made.

OPEN-HEARTH PLANT

This section describes the distribution of water to two 100-ton fixed open-hearth furnaces, from the distributing station, which is supplied by hard- and soft-water lines from the central pumping station.

Figure 8 shows the diagrammatic layout of the plant. The incoming 6-in. dia. soft-water line delivers to the cold-water pump suction tank, and is controlled by a ball float for make-up purposes. The 4-in. dia hard-water line serves the supply points for ordinary services, but is connected to the soft-water distributing station for use in emergencies. The distribution station consists of cold- and hot-water pumps, cooling tower, and an overhead storage tank. The three cold-water pumps, each of 21,000 gal./hr. capacity, feed the overhead tank, which is equipped with a float valve automatically controlling delivery from the pumps.

The reinforced concrete circular storage tank contains 100,000 gallons of water, and is 100 ft. above ground level and 78 ft. above the level of the furnace-charging platform. The 14-in. dia. delivery pipe from the tower to the furnaces feeds into a 10-in. dia. header main, from which tappings are taken to the various cooling points at and around the furnaces. The 14-in. dia. delivery main from the pumps is arranged so that, if necessary, the tower can be by-passed, and furnace cooling water pumped direct to the header main at the furnaces.

The return water is collected in tundishes and gravitates back to the hot pump suction tank, from which it is pumped by three centrifugal pumps, each of 21,000 gal./hr. capacity, to the cooling tower. The tower is of reinforced concrete construction, natural-draught type, 100 ft. high, and capable of dealing with 150,000 gal./hr. The cooled water gravitates to the cold pump suction tank for re-circulating.

A 4-in. dia. connection to the furnace waste-heat boilers is taken from the incoming 6-in. dia. soft-water line, which delivers into the boiler-feed tank and is controlled by a float valve. Supply can also be obtained through an auxiliary pipe connected to the furnace cooling-water circuit.

It will be noted from the foregoing and from Fig. 10 that comprehensive arrangements are made for alternative supply, as insurance against failure involving loss of output and damage to coolers. The loss of water through evaporation and other causes is about 1460 gal./hr., with a total flow of 50,000 gal./hr. through the two furnaces.

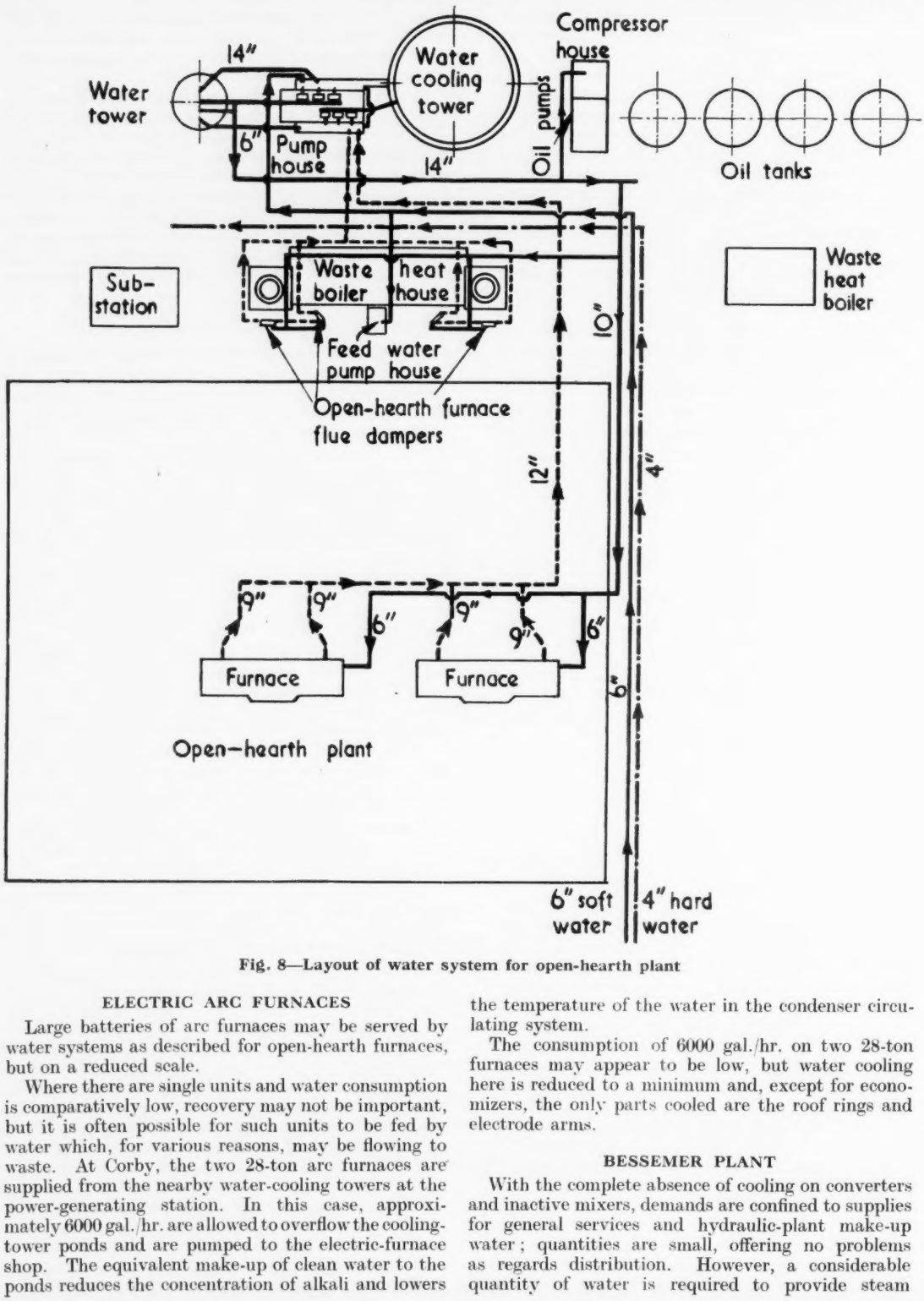


Fig. 8—Layout of water system for open-hearth plant

ELECTRIC ARC FURNACES

Large batteries of arc furnaces may be served by water systems as described for open-hearth furnaces, but on a reduced scale.

Where there are single units and water consumption is comparatively low, recovery may not be important, but it is often possible for such units to be fed by water which, for various reasons, may be flowing to waste. At Corby, the two 28-ton arc furnaces are supplied from the nearby water-cooling towers at the power-generating station. In this case, approximately 6000 gal./hr. are allowed to overflow the cooling-tower ponds and are pumped to the electric-furnace shop. The equivalent make-up of clean water to the ponds reduces the concentration of alkali and lowers the temperature of the water in the condenser circulating system.

The consumption of 6000 gal./hr. on two 28-ton furnaces may appear to be low, but water cooling here is reduced to a minimum and, except for economizers, the only parts cooled are the roof rings and electrode arms.

BESSEMER PLANT

With the complete absence of cooling on converters and inactive mixers, demands are confined to supplies for general services and hydraulic-plant make-up water; quantities are small, offering no problems as regards distribution. However, a considerable quantity of water is required to provide steam

and condenser cooling water for the turbo-blowers.

The steam-generating plant adjacent to the Bessemer shop contains six water-tube boilers, each rated at 42,000 lb./hr. of steam at 365 lb./sq. in. (gauge) pressure and 650° F. superheated steam temperature. This boiler plant is linked up with the blast-furnace boilers supplying steam to all sections of the works. Feed-water make-up in addition to condensate amounts to 230,000 gal./day.

Air for the blowing of converters is provided by one of two turbo-blowers housed in a station with a 7500-kW. turbo-alternator. The two blowers, each capable of delivering 28,000 cu. ft./min. of free air at 35 lb./sq. in. (gauge), are driven by steam turbines equipped with surface condensers, each dealing usually with 26,800 lb. of steam per hour, maintaining a vacuum of 28 in. of mercury ; the area of the cooling surface is 3200 sq. ft., requiring 198,000 gal. of cooling water per hour.

The turbo-alternator, also driven by a steam turbine, requires 540,000 gal. of water per hour for cooling the surface condenser, which deals with 67,000 lb. of steam per hour, maintaining a vacuum of 28 in. of mercury.

There are three natural-draught cooling towers, two of which, having a combined capacity of 56,000 gal./hr., serve the turbo-alternator ; the third, which can deal with 25,000 gal./hr., serves either of the two blowers. The make-up water required for all the cooling towers is 12,540 gal./hr.

The layout of piping for circulating water and condensate follows the usual practice.

ROLLING-MILL PLANT

Adequate and constant supplies of water to rolling mills are perhaps less vital than to other sections of iron and steel works plant, but the actual problems of water saving on the mills are far greater. Supply and circulation for reheating furnaces follow the same system as for open-hearth furnaces, where water remains clean and the only losses suffered are from evaporation.

In considering the layout of a system for a group of rolling mills, the chief concern is the cleaning and recovery of mill-return dirty water, which is contaminated with scale. In some plants all the mill-return water is pumped from the works to outlying ponds, where the scale is allowed to settle naturally and, after a period of rest, the water is brought back into circulation. Site conditions may not permit this, and it then becomes necessary to place small ponds or concrete tanks adjacent to the mills. If these are too small and the scale does not have time to settle, water is re-circulated with particles in suspension ; line filters of various types and sizes have been tried, but have not been effective. It is understood that this very real problem of the rapid separation of scale in large quantities of water is receiving thorough investigation. Layout of hard- and soft-water mains from the central station to the rolling mills are shown in Figs. 9 and 10.

In the following descriptions of systems operating on groups of rolling mills, the main points of applications are :

Reheating furnace cooling
Cooling of roll barrels and necks
Lubrication of synthetic bearings for roll necks
De-scaling of bars or strip with high-pressure water.

Figure 11 shows diagrammatically a local distributing station feeding a group of rolling mills, comprising a 40-in. blooming mill, a 32-in. single-stand bar mill, a 4-stand 24-in. continuous mill, and two single-stand 2-high 24-in. mills in tandem. The station also feeds a separate mill for the production of strip for tube manufacture ; this comprises two 22-in. 3-high roughing stands, two 19-in. 2-high intermediate stands and four 20-in. 2-high finishing stands, and two reheating furnaces. The station is fed from the works central station by 12-in. dia. and 6-in. dia. hard- and soft-water mains, respectively. The overhead storage tank contains hard- and soft-water compartments providing storage for 45,000 gallons of hard and 15,000 gallons of soft water.

Soft water is used only for reheating furnace cooling and various other purposes. The circulating system follows the general lines, and consists of gravity return from the mills to a hot-water tank, from which the hot water is re-circulated through a cooling tower by two 500 gal./min. centrifugal pumps. The cold water is then pumped back to the overhead storage tank for re-distribution.

The hard-water circulating system, together with supply lines, is also shown in Fig. 11. All water for actual rolling-mill purposes must find its way back to the distributing station *via* the scale pits. There are two pits, one of which serves the 40-in. mill and the group of mills connected with it, and the other serves the strip mill. In both pits, the water flows over weirs before joining the common return to another scale pit at the station. Two centrifugal pumps of 2500 gal./min. capacity deliver to the overhead storage tank. Supplies for de-scaling are also taken from this system, and discharge into a pump suction tank at the strip mill. The de-scaling system is simple, consisting of two $3\frac{1}{2}$-in. 12-stage centrifugal pumps, each capable of delivering 200 gal./min. against 1000 lb./sq. in. direct to spray nozzles at various points in the strip mill.

Three mills are equipped with synthetic roll-neck bearings, and the 40-in. and 19-in. mills receive water from the clean-water mains from the central station ; in addition to supplying the necessary clean water to these roll necks, the extra supply forms part of the make-up water to the system. Under present conditions, the 24-in. mill synthetic roll-neck bearings are supplied with dirty water from the circulating system. All other roll-neck bearings are bronze, with the exception of the 20-in. continuous strip mill, which has roller bearings.

The re-distribution of water containing scale in suspension is the most undesirable feature of these systems, especially in rolling mills where synthetic roll-neck bearings are used, and where the hydraulic de-scaling of bars is necessary. The features prevailing in this plant are at present unavoidable but, in the circumstances, the life of synthetic roll-neck bearings is reasonably long, in spite of the adverse conditions. Apart from the heavy maintenance of impellers in high-pressure de-scaling pumps, the

Fig. 9.—Layout of hard-water mains to Bessemer plant, rolling mills, and open-hearth plant

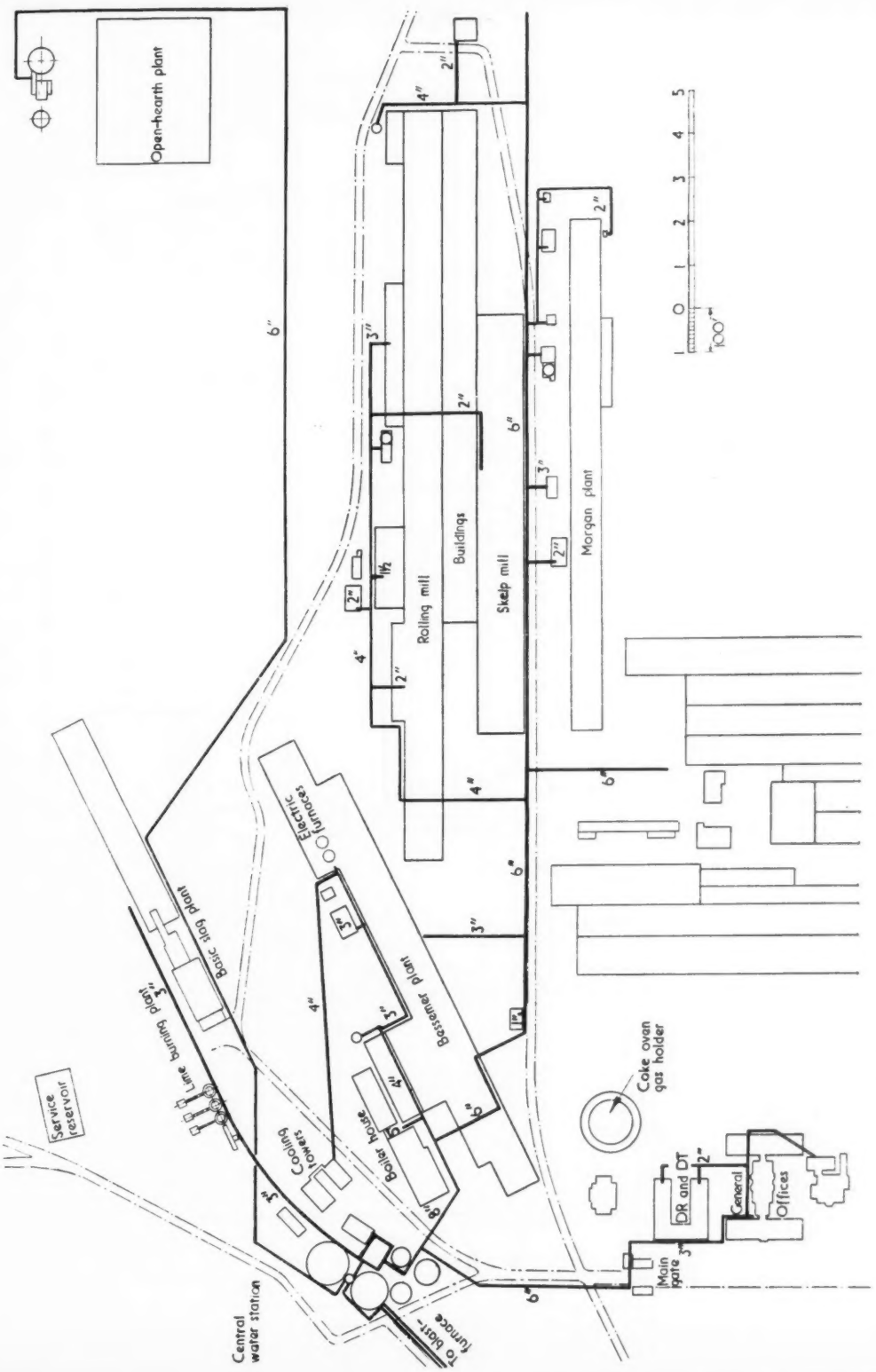


Fig. 10—Layout of treated-water mains to Bessemer plant, rolling mills, and open-hearth plant

periodic choking of spray nozzles prevents efficient de-scaling, which is a vital factor in the production of clean strip.

Isolated from this group of mills is a 10–12-in. continuous hot-strip mill, equipped with Morgoil roll-neck bearings, for the production of strip for tube manufacture. This plant has its own distributing station and is similar to the one previously described, but is without a cooling tower. The layout of the station and pipe-work is shown in Fig. 12. The overhead tank storage capacity for hard and soft water is 43,000 and 15,000 gal., respectively. The incoming supplies for make-up purposes consist of 600 gal. of soft water and 5000 gal. of hard water per hour. The overflow from the dirty-water suction tanks flows to the works main drain.

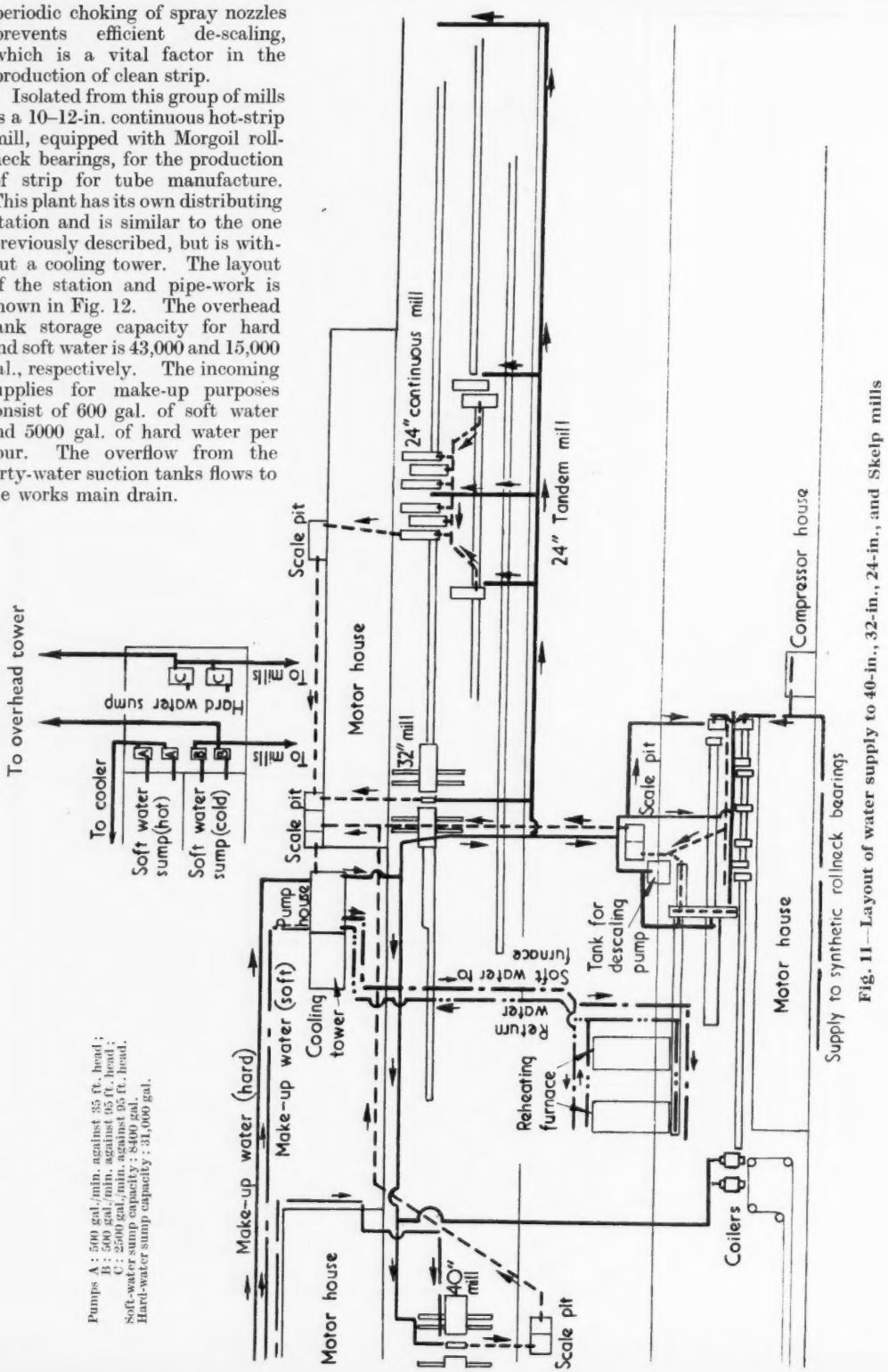


Fig. 11—Layout of water supply to 40-in., 32-in., 24-in., and Skelp mills

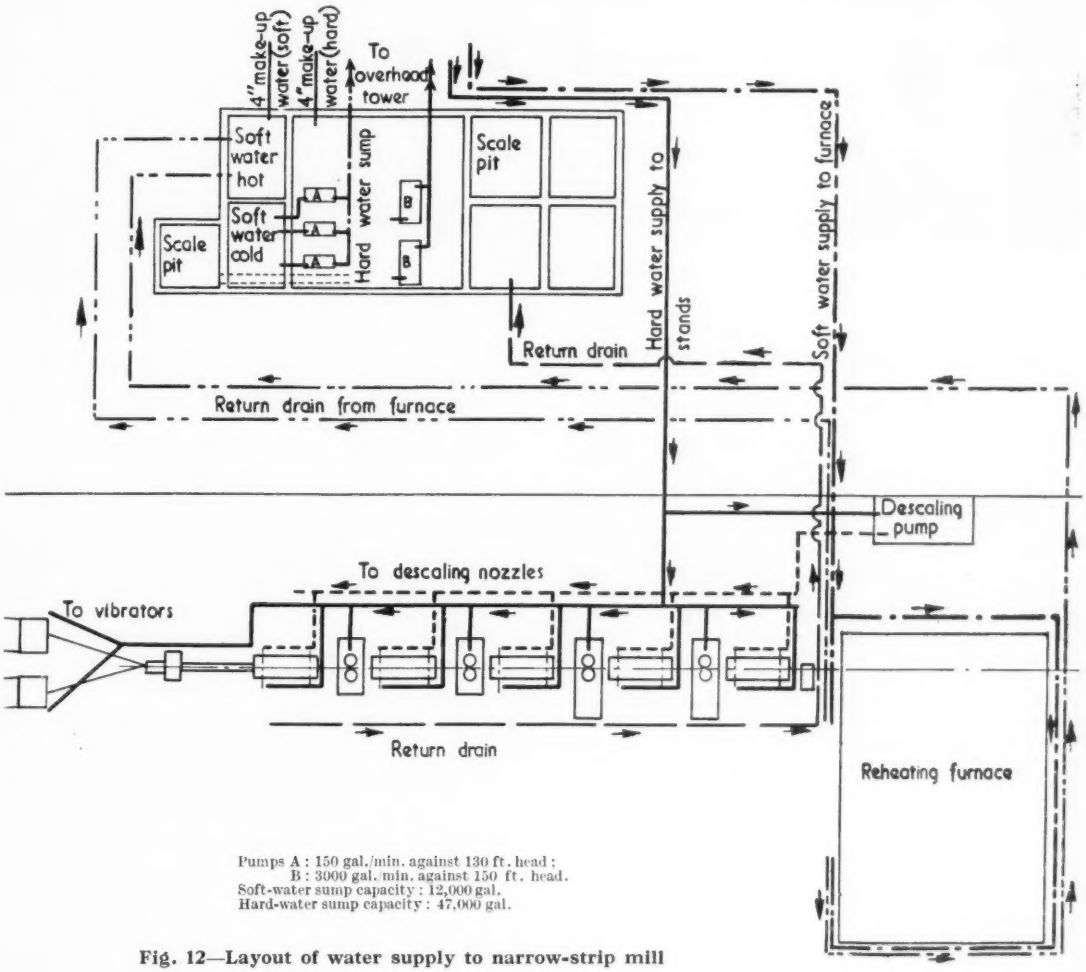


Fig. 12—Layout of water supply to narrow-strip mill

The hard water is delivered by a 300 gal./min. centrifugal pump, against a head of 150 ft., into the storage tank, from which it is fed to the mill by a 6-in. dia. pipe. Similarly, soft water is pumped at the rate of 400–450 gal./min. to the tower, for circulation to the mill reheating furnace. As there is no cooling tower in this installation, slight reductions in temperature are effected by sprays over each of the suction tanks ; the large quantity of water in circulation results in a slow rate of temperature rise. The mill works only 16 hours per day, and temperatures at the end of the working period are in the region of 112–120° F. for hard water, and 138–178° F. for soft water. Here also, dirty water is used for the de-scaling of bars, and the same difficulties of maintenance of pump impellers and choking of spray nozzles are encountered.

CONCLUSIONS

In the foregoing descriptions of water systems in a large iron and steel works, it is not convenient to show the layout of pipe-lines other than by line diagram. This method of illustration can create the impression that the arrangement of pipe-work is ideal, whereas in reality this may not be the case. It is not unusual to find that, owing to additions to the plant, the carrying capacity of mains becomes too low, and invariably duplicate mains are installed. The repetition of this over a period of years often results in a most complicated and uneconomical method of distribution. It is well worth the extra initial cost, in laying down steelworks pipe systems, to provide mains with good margins of capacity in anticipation of additional future demands.

All the quantities mentioned are average consumptions. They are measured by meters, with readings taken daily and recorded.

Acknowledgments

The author wishes to express his thanks to many of his colleagues who assisted him in the preparation of this paper.

N E W S

ANNOUNCEMENTS AND NEWS OF SCIENCE AND INDUSTRY

THE IRON AND STEEL INSTITUTE

Special Meeting in Glasgow, 1950

The Council of The Iron and Steel Institute have accepted an invitation from the West of Scotland Iron and Steel Institute to hold a Special Meeting in Glasgow from Tuesday, 12th, to Friday, 15th September, 1950.

The Lord Provost of Glasgow has kindly agreed to be Patron. Reception, Executive, and Ladies Committees have been formed, the Chairmen being Sir Andrew McCance, D.Sc., LL.D., F.R.S., Mr. W. Barr, A.R.T.C., F.I.M. (President of the West of Scotland Iron and Steel Institute), and Lady McCance. Mr. P. W. Thomas, Secretary of the West of Scotland Iron and Steel Institute, has consented to be Honorary Secretary; Mr. R. A. Hillis, of Colvilles, Ltd., is kindly helping with the arrangements in Glasgow.

It will be necessary to limit the total number of Members and Ladies attending the Meeting to a maximum of 400.

PROGRAMME

The following is the programme for the Meeting :

TUESDAY, 12TH SEPTEMBER

10.0 A.M. to 10.15 A.M.
Members and Ladies
Formal welcome by Sir Andrew McCance, D.Sc., LL.D., F.R.S., at the Institution of Engineers and Shipbuilders in Scotland

10.15 A.M. to 12.15 P.M.
Members
Joint technical session with the West of Scotland Iron and Steel Institute (*see* p. 455)
Ladies
Exc. 1—Morning coffee and mannequin parade at Daly's

12.30 for 1.0 P.M. to 2.15 P.M.
Members and Ladies
Luncheon at the Central Hotel. (Max. number 400)

2.30 P.M. to 5.0 P.M.
Members
Visit to *one* of the following works :
Exc. 2—Stewarts and Lloyds, Ltd., Clydesdale Works, Mossend
Exc. 3—Clyde Alloy Steel Co., Ltd., Motherwell
Exc. 4—G. and J. Weir, Ltd., Cathcart
Exc. 5—Albion Motors, Ltd., Scotstoun
Ladies
Afternoon free ; OR take part in *one* of the following excursions :
Exc. 6—Visit to the Scottish National Memorial to David Livingstone, Blantyre, with tea
Exc. 7—Conducted bus tour in Glasgow, with tea

8.0 P.M. to 11.30 P.M.
Members and Ladies
Reception by the Lord Provost and Magistrates in the City Chambers
(*Dress :* Evening dress, with decorations)

WEDNESDAY, 13TH SEPTEMBER

9.30 A.M. to 5.0 P.M.
Ladies
Exc. 8—All-day motor bus tour to Loch Lomond, the Trossachs, and Stirling, with lunch and tea

10.0 A.M. to 12 NOON
Members
Morning free

12.15 to 5.0 P.M.
Members
Take part in one of the following visits, with lunch at the works :
Exc. 9—W. Beardmore and Co., Ltd., Parkhead
Exc. 10—Lanarkshire Steel Co., Ltd., Motherwell
Exc. 11—Babcock and Wilcox, Ltd., Renfrew
Exc. 12—R. B. Tennent, Ltd., and Lamberton and Co., Ltd., Coatbridge

7.15 for 8.0 P.M. to 1.0 A.M.
Members and Ladies
Dinner and Dance at the Central Hotel. (Max. number 400)
(*Dress :* Evening dress or dinner jacket)

Special Notice

Owing to a withdrawal of overtime work which has been imposed by a section of the Printing Industry the *Journal*, in common with other periodicals, is now reduced in size.

So long as the dispute continues the number of pages must be reduced, and delays in publishing may be unavoidable.

THURSDAY, 14TH SEPTEMBER

9.30 A.M. to 6.0 P.M.
Ladies
Exc. 13—All-day motor bus tour to Edinburgh and the Forth Bridge, with lunch at the Caledonian Hotel, Edinburgh

9.30 A.M. to 12.30 P.M.
Members
Visit to *one* of the following works :
Exc. 14—Colvilles, Ltd., Clyde Iron Works, Cambuslang
Exc. 15—Colvilles, Ltd., Clydebridge Steel Works, Cambuslang
Exc. 16—Harland and Wolff, Ltd., Scotstoun
Exc. 17—Duncan Stewart and Co., Ltd., Bridgeton

12.30 for 1.0 P.M. to 2.15 P.M.
Members
Luncheon at the Grosvenor Restaurant, Glasgow
2.30 to 5.0 P.M.
Members
Visit to *one* of the following works :
Exc. 18—Colvilles, Ltd., Clyde Iron Works, Cambuslang
Exc. 19—Colvilles, Ltd., Clydebridge Steel Works, Cambuslang
Exc. 20—Colvilles, Ltd., Glengarnock
Exc. 21—Anderson, Boyes and Co., Ltd., Motherwell
Evening
Members and Ladies
Evening free

FRIDAY, 15TH SEPTEMBER

9.30 A.M. to 6.0 P.M.
Members and Ladies
Exc. 22—All-day excursion on the River Clyde in S.S. *Queen Mary II* ; visit to John Brown and Co., Ltd. ; thence sail through the Kyles of Bute, returning to Glasgow by train from Fairlie
Evening
Members and Ladies
Free.

TECHNICAL SESSION

The joint technical session with the West of Scotland Iron and Steel Institute will be held in the Rankine Hall of the Institution of Engineers and Shipbuilders in Scotland, at 39 Elmbank Crescent, Glasgow, C.2.

The detailed programme is as follows :

10.15 A.M.–11.15 A.M. Presentation and discussion of the paper "*The Reduction of Lump Ores*," by R. Wild and H. L. Saunders (June 1950)

11.15 A.M.–12.15 P.M. Presentation and joint discussion of the papers "*The Distribution of Temperature in Ingot Moulds and Its Relation to Ingot Structure*," by I. M. Mackenzie and A. Donald (Sept. 1950) ; "*Ingot Heat Conservation : Time Studies from Casting to Rolling*," by A. V. Brancker, J. Stringer, and L. H. W. Savage (Jan. 1950) ; "*Ingot Heat Conservation : Mould and Ingot Surface Temperature Measurements*," by A. V. Brancker (July 1950).

A report of the discussion will be published in the *Journal* in due course.

A Paper on "*The Production of Steel Plates in Scotland*," by J. A. Kilby, is being published in the September issue of the *Journal* for the Meeting, but it will not be formally presented or discussed.

Symposium on High-Temperature Steels and Alloys for Gas Turbines

A Symposium on High-Temperature Steels and Alloys for Gas Turbines will take place under the Chairmanship of Mr. J. R. Menzies-Wilson, O.B.E., President of The Iron and Steel Institute, in the Lecture Theatre of The Institution of Civil Engineers, Great George Street, London, S.W.1, on Wednesday and Thursday, 18th and 19th October, 1950. The Sessions will commence at 10.0 A.M. and 2.30 P.M. on both days.

A Dinner for those attending the Symposium will be held at the Hyde Park Hotel, Knightsbridge, London, S.W.1, on Wednesday, 18th October, 1950, at 7.0 for 7.30 P.M.

Buffet Luncheon will be available on both days.

Attendance of Non-Members—Non-Members of The Iron and Steel Institute, whether friends of Members or not, will be welcome at the Meetings and functions, on the same terms as Members.

Participants will be required to pay the following charges in connection with the Symposium and related functions :

A Registration Fee of 10*s.* 0*d.* per person.

The Papers—The papers presented at the Symposium and the discussions during the Meeting will be issued as a single bound volume (No. 43 in the Special Report Series of The Iron and Steel Institute), the published price of which will be £3 3*s.* 0*d.* (post free). Orders received before the Meeting, if accompanied by a remittance, will be supplied at the reduced rate of £2 2*s.* 0*d.* (post free), and those attending the Meeting who purchase a volume beforehand will be provided with a set of advance copies of the papers without extra charge. Advance copies will not be supplied separately. A list of the titles of the papers will be published in the September issue of the *Journal*.

Buffet Luncheons—The charge for the Buffet Luncheons on the two Meeting days will be 6*s.* 0*d.* per person per day.

Dinner—The price of tickets for the Dinner on the Wednesday will be £1 5*s.* 0*d.* This will include gratuities but not drinks.

Fifth Hatfield Memorial Lecture

The Fifth Hatfield Memorial Lecture will take place in association with the Symposium, and will be delivered by Air Commodore Sir Frank Whittle, K.B.E., C.B., D.Sc., F.R.S., in the Lecture Theatre of The Institution of Electrical Engineers, Savoy Place, Victoria Embankment, London, W.C.2, on the evening of Tuesday, 17th October, 1950, at 8.30 P.M. Mr. J. R. Menzies-Wilson, O.B.E., President of The Iron and Steel Institute, will preside.

There will be no charge for attendance at this lecture, but those proposing to be present will be provided with tickets of admission.

A circular, containing full details of the meeting and the reply form, is distributed with this issue of the *Journal*. Further copies may be had on application to the Secretary.

Autumn General Meeting, 1950

The Autumn General Meeting will be held in London, on Wednesday and Thursday, 15th and 16th November, 1950.

NEWS OF MEMBERS

▶ Mr. Y. M. P. DARDEL has left the Centre de Documentation Sidérurgique, Paris, to take up an appointment with the Climax Molybdenum Co., Zürich.

▶ Dr. S. HARPER has left the University of Birmingham and is now at the Institute for the Study of Metals, University of Chicago, U.S.A.

▶ Mr. N. HASLAM has been appointed Metallurgist at the British Iron and Steel Research Association, Sheffield.

▶ Mr. A. W. HOTHERSALL has been awarded the Gold Medal of the Electrodepositors' Technical Society.

▶ Mr. R. F. HUDSON has left the Commonwealth Aircraft Corporation to take up an appointment as Metallurgist with the Melbourne and Metropolitan Tramways Board, Preston, Victoria.

▶ Mr. G. H. JACKSON has been appointed Chief Metallurgist to the Amalgamated Dental Engineering Industries, Ltd., Walton-on-Thames.

▶ G. JEFFORD has been awarded the B.Sc. degree of the University of Wales.

▶ Mr. B. KRISHNAMURTHY has joined the staff of the Indian Aluminium Co., Ltd., West Bengal, India.

▶ Mr. I. B. MCKNIGHT has been awarded the B.Sc.(Met.) degree of the University of Leeds and has been appointed

a Supervisor in the Smelting and Refining Department of the Associated Lead Manufacturers, Millwall.

▶ Mr. W. K. B. MARSHALL has left the Welding Research Association, to take up an appointment with Messrs. Rockweld, Ltd., Croydon.

▶ Mr. R. L. MORTON has been awarded the B.Sc. degree of the University of Glasgow, and has been elected an Associate of the Institution of Metallurgists.

▶ Mr. J. NAYSMITH has left Messrs. Stewarts and Lloyds, Ltd., and has been appointed Supervisor at the Millwall Lead Works of the Associated Lead Manufacturers, Ltd.

▶ Mr. J. A. PARDOE has left D. Napier and Son, Ltd., Liverpool, to take up an appointment as Metallurgist in the Department of Atomic Energy, Springfields Factory, Salwick, Nr. Preston.

▶ Mr. R. TALWAR has joined the staff of Messrs. Martin Burn, Ltd., Burnpur, India.

▶ Mr. H. TAYLOR has left the Millom and Askam Hematite Iron Co., Ltd.

Obituary

Mr. H. C. LOVING, on the 7th February, 1950.

Mr. F. CALVERT, of the Townley Metallurgical Company, Leeds, on 25th March, 1950.

Sir ROBERT CRICHTON, C.B.E., Vice-Chairman of the Lancashire Steel Corporation, Ltd., on 8th May, 1950.

Mr. N. P. BEDSON, Chief Engineer, Messrs. Richard Johnson and Nephew, Ltd., on the 22nd May, 1950.

Mr. E. B. CHRISTMAS, Managing Director of Messrs. Christmas and Walters, Ltd., on 31st May, 1950.

Mr. R. GRIFFITHS, Senior Lecturer in the Department of Metallurgy, University College, Swansea, on 24th June, 1950.

CONTRIBUTORS TO THE JOURNAL

P. E. Brookes, B.Met., Ph.D.—A member of the X-ray section of the Research and Development Department of The United Steel Companies Limited, Stocksbridge. Dr. Brookes was born in 1926, and he was educated at Woodhouse Grammar School and at the University of Sheffield. He graduated with the degree of Bachelor of Metallurgy in 1946. He then carried out post-graduate research work on problems associated with the cold deformation of steel by drawing and rolling, for which he was awarded the degree of Ph.D., in 1949, and was also awarded the Brunton Medal. He took up his present appointment in 1949.

L. Bourne, B.Met., A.I.M.—A member of the staff of the Mechanical Working Division of the British Iron and Steel Research Association. Mr. Bourne was educated at Wath-on-Dearne Grammar School and at the University of Sheffield. He gained the degree of Bachelor of Metallurgy in 1943.

From 1943 until 1945 he was engaged on research for the Safety-in-Mines Research Board, and in 1945 he joined the British Iron and Steel Research Association, working first in the Department of Metallurgy at Sheffield University, and subsequently at the Metal Flow Research Laboratory of the Association, at Sheffield.

D. V. Wilson, M.A., F.R.I.C.—A research worker at the University of Sheffield, under a grant from the British Iron and Steel Research Association. Mr. Wilson was born in 1916, and was educated at Oundle School and at Corpus Christi College, Cambridge University. He graduated in Natural Sciences (Part II—Metallurgy) with honours, in 1938. For one year he was a Research Assistant at the British Non-Ferrous Metals Research Association, and in 1939 he was transferred to the laboratory of the Royal Ordnance Factory at Birtley, where he served as Senior Assistant, and later as Chief Metallurgist.

In 1946 Mr. Wilson was a member of technical missions visiting Germany, the U.S.A., and Canada, as a representative of the Armaments Design Department of the Ministry of Supply. He joined the research team at Sheffield University in 1947 on receiving a bursary from the British Iron and Steel Research Association.

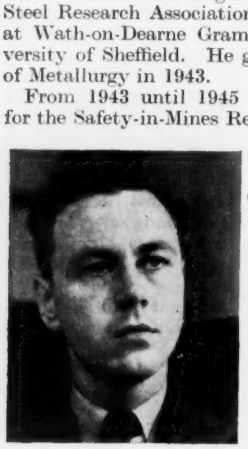
U. V. Bhat, B.Sc.(Met.), Ph.D.—Professor of Metallurgy in the College of Mining and Metallurgy, Benares Hindu University. Dr. Bhat was educated at the Canara High School and Government College, Mangalore, and at the Benares Hindu University, where, in 1932, he obtained the degree of B.Sc. in Metallurgy, with first-class honours. In the same year he was appointed Assistant Professor of Metallurgy at the University.

In 1945 Dr. Bhat was awarded a Holkar Fellowship for higher studies abroad. He came to England and carried out research on the deformation of steel under Professor J. H. Andrew, at Sheffield University. In 1947 he was awarded the degree of Ph.D. for his work on this subject. He returned to India and took up his present appointment in 1948.

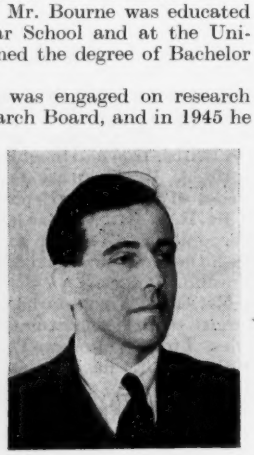
A. L. Cude, B.Sc.—A member of the staff of the Plant Engineering Division of the British Iron and Steel Research Association. Mr. Cude received his technical education at the University of Birmingham, where he graduated, in 1942, with an honours degree in oil engineering and refining.

He then joined the staff of the Research and Development Department of the Anglo-Iranian Oil Company, where he was engaged mainly on pilot-plant operations. He took up his present appointment with the Research Association in the early part of 1947.

T. H. Harris, A.Met.—Manager of the Electric-Melting Shop of the Brymbo Steelworks Limited, Wrexham, North Wales. Mr. Harris was educated at Rossall School, and from 1930 to 1934 he took part in the apprenticeship scheme of The United Steel Companies Limited, during which period he attended Sheffield University and there obtained the Associateship in Metallurgy.



P. E. Brookes



L. Bourne

D. V. Wilson

U. V. Bhat

D. J. O. Brandt

W. H. Everard

In 1935 he was appointed Shift Manager at the Electric-Melting Shop of Messrs. Samuel Fox and Co., Ltd., Stocksbridge. He remained there until 1939, when he was appointed to his present position. After the last war he spent two and a half years with the Allied Control Commission in Germany, concerned mainly with work on steelplant reparations.

D. J. O. Brandt, A.R.S.M., B.Sc., A.I.M.—Senior Scientific Officer in the Steelmaking Division of the British Iron and Steel Research Association. Mr. Brandt was educated at Clifton College, Bristol, and at the Royal School of Mines, London, where he graduated in 1941. He then joined Murex Limited of Rainham, Essex, where he was engaged in the manufacture of low-carbon ferro-chromium.

Mr. Brandt left Murex in 1942 when he was appointed to the Armour and Bullet Proof Plates Section of the Department of Tank Design, Ministry of Supply. He remained there until 1945 when he joined Messrs. John Miles and Partners (London) Ltd., for whom he carried out experimental work on the use of oxygen in steel manufacture. He took up his present position early in 1948, and is continuing his work on oxygen under the auspices of the Research Association.

W. H. Everard—Manager of the Steel Melting Plants of Messrs. Edgar Allen and Co., Ltd., Sheffield. Mr. Everard joined the laboratory staff of the Company in 1913 and was later appointed Assistant Manager in the Open-Hearth and Electric Melting Department. In 1920 he was appointed personal assistant to the Steel Melting Plant Manager.

He visited South Africa, in 1934, to erect and operate a steel foundry at Benoni, on behalf of Messrs. Standard Brass, Iron, and Steel Co., Ltd. He was placed in full charge of this project, and trained South Africans in the technique of sand control, moulding, steel melting, casting, and heat-treatment. He returned to Messrs. Edgar Allen and Co., Ltd., in 1937.

Mr. Everard was appointed to his present position in 1946, and is now responsible for the Steel Melting Plants comprising electric-arc furnaces, cupolas, and side-blown converters, and for the Foundry Heat-Treatment Department. He is a member of the Electric Process Sub-Committee of the Steelmaking Division, and the Melting Sub-Committee of the Steel Castings Division of the British Iron and Steel Research Association.

BRITISH IRON AND STEEL RESEARCH ASSOCIATION

Committee Changes

Dr. C. SYKES, F.R.S., Director of Research, Brown-Firth Research Laboratories, has retired from the chairmanship of the Divisional Panel of the Metallurgy General Division, and has been succeeded by Mr. W. BARR, Chief Metallurgist, Messrs. Colvilles, Ltd.

Mr. G. H. JOHNSON, of the Kettering Iron and Coal Co., Ltd., has retired from the chairmanship of the Divisional Panel of the Iron Making Division, and Mr. W. C. BELL, of Messrs. Stewarts and Lloyds, Ltd., has accepted the chairmanship. Mr. Johnson has agreed to act as deputy chairman for a year.

Staff

Dr. A. V. BRANCKER, of the Fuel Section of the Plant Engineering Division, left the Association on 20th May, 1950.

THE IRON AND STEEL ENGINEERS GROUP

Engineering Committee, 1950–51

Chairman

Mr. C. H. T. WILLIAMS	Park Gate Iron and Steel Co., Ltd.

Members

Mr. W. F. CARTWRIGHT	Steel Company of Wales, Ltd.
Mr. J. L. GASKELL	Appleby-Frodingham Steel Co., Ltd.
Mr. F. B. GEORGE	Consett Iron Co., Ltd.
Mr. W. M. LARKE	Stewarts and Lloyds, Ltd.
Mr. P. A. LEE	Arthur Lee and Sons, Ltd.
Mr. G. S. MARTIN	Lanarkshire Steel Co., Ltd.
Mr. J. E. OWSTON	F. B. Engineers, Ltd.
Mr. W. J. POOL	British Thomson-Houston Co., Ltd.
Mr. F. SANITER	United Steel Companies, Ltd.
Mr. B. THORNTON	Wellman Smith Owen Engineering Corporation, Ltd.
Mr. W. UDALL	Brightside Foundry and Engineering Co., Ltd.
Mr. P. WRIGHTSON	Head Wrightson and Co., Ltd.

Ex-Officio

Mr. J. R. MENZIES-WILSON	President, The Iron and Steel Institute
Mr. J. MITCHELL	Hon. Treasurer, The Iron and Steel Institute
Mr. H. H. MARDON	British Iron and Steel Research Association
Mr. I. S. SCOTT-MAXWELL	British Iron and Steel Federation.

INSTITUTE OF METALS

Capper Pass Awards

The Capper Pass Awards Adjudicating Committee has made the following awards for 1949, on behalf of the Councils of the Institution of Mining and Metallurgy and of the Institute of Metals.

J. MATTER and M. LAMOURDEDIEU (Société Centrale des Alliages Légers, Issoire (Puy-de-Dôme), France), £50 jointly for a paper on "The New Factory of the Société Centrale des Alliages Légers at Issoire (Puy-de-Dôme) for the Working of Light Alloys," published in the *Journal of the Institute of Metals*, 1949, vol. 75, August.

G. CHAD NORRIS (West African Gold Corporation, Ltd.) £50 for a paper on "Gold Concentration at the Amalgamated Banket Areas Reduction Plant," published in the *Bulletin of the Institution of Mining and Metallurgy*, 1949, No. 516, November.

E. SCHEUER (International Alloys, Ltd., Aylesbury, Bucks), £50 for a paper on "Modern Billet Casting, with Special Reference to the Solidification Process," published in the *Journal of the Institute of Metals*, 1949, vol. 76, October.

H. L. TALBOT (Anglo-American Corporation of South Africa, Ltd.) and H. N. HEPKER (Central Research Laboratory, N'Kana, Northern Rhodesia), £50 jointly for a paper on "Investigations on the Production of Electrolytic Cobalt from a Copper–Cobalt Flotation Concentrate," published in the *Bulletin of the Institution of Mining and Metallurgy*, 1949, No. 514, September.

The Capper Pass Awards, which are made annually from a sum of £200 per annum placed at the disposal of the Councils of the Institution of Mining and Metallurgy and of the Institute of Metals by Messrs. Capper Pass and Son, Ltd., Bristol, are as follows:

(*a*) £100 per annum, for one or more awards to authors of papers on some aspect of non-ferrous extraction metallurgy.

(*b*) £100 per annum, for one or more awards to authors of papers relating to some process or plant used in the fabrication of non-ferrous metals contributed by persons engaged full time in industrial practice.

The Adjudicating Committee will meet early in 1951, to consider all papers published by both societies during the year 1950. Papers on extraction metallurgy should be submitted, in duplicate, to the Secretary of the Institution of Mining and Metallurgy, Salisbury House, Finsbury Circus, London, E.C.2, and papers on fabrication should be submitted to the Secretary of the Institute of Metals, 4 Grosvenor Gardens, London, S.W.1.

MEMOIRS

Martin Alexander, B.Sc., died in Leigh Hospital on March 15th, 1950, after a sudden and brief illness. From 1928–35 he studied at University College, Swansea, where he graduated with an honours degree in metallurgy and carried out some post-graduate research under Dr. C. A. Edwards, F.R.S.

In 1935 he joined the staff of the Research Department, Woolwich, and during World War II, was seconded to the Ordnance Board. For a brief period at the end of hostilities, he was metallurgical adviser to the Control Commission in Germany. He joined the Department of Atomic Energy at Risley in 1946.

Mr. Alexander was co-author of Section XI of the Sixth Report on the Heterogeneity of Steel Ingots. He became a Member of The Iron and Steel Institute in 1937 and was a Member of the Institute of Metals.

Noel P. Bedson, B.Sc., A.M.I.C.E., M.I.E.E., died on 22nd May, 1950. He was educated at Manchester University, graduating in Engineering in 1909. He spent the next five years at the British Westinghouse, and in Germany at Gütehoffnungshütte in Operhausen, and at Siemens Schuckert in Berlin and Liège.

In 1914, Mr. Bedson became Chief Engineer with Messrs. Richard Johnson and Nephew, Ltd., where his grandfather and father had both worked. Shortly before his death he had developed a new rod rolling mill. Mr. Bedson's wide experience and knowledge of rod and wire production were recognized both in this country and abroad.

He was elected a Member of The Iron and Steel Institute in 1914.

Frank Calvert, of the Townley Metallurgical Company, died on 25th March, 1950. He was born in 1892 and educated at Cockburn High School. At the age of 15 he joined the laboratory staff of Messrs. Taylor Brothers and Co., Ltd., Iron and Steel Works, Leeds, and attended classes at Leeds Technical College, and later at Leeds University. When only 18 years old he became Steel Plant Manager with the same firm and later transferred to their Trafford Park Steel Works, Manchester, in the same capacity.

In 1922 Mr. Calvert started business on his own account as the Townley Metallurgical Company, Leeds, and continued in this capacity until his death.

He was elected a Member of The Iron and Steel Institute in 1947.

E. B. Christmas died on the 31st May, 1950, at the age of 76. He was educated at Ardingly College and started his career with the London and South Western Railway. Later he joined the firm of Wellman Seaver Head and Co. (now the Wellman Smith Owen Engineering Corporation, Ltd.) and whilst with them he installed the first mechanical open-hearth charging machine in this country.

In about 1910 he started business in Sheffield on his own account as British representative of Messrs. Julian Kennedy, Sahlin and Co., Ltd. and the Knox Pressed and Welded Steel Co. of Pittsburgh, U.S.A. He also represented the Pearson and Knowles Coal and Iron Co. When the International Construction Co., Ltd. became successors to Julian Kennedy, Sahlin and Co., Ltd., he became a Director of the Company.

In 1921 Mr. Christmas founded the firm of Christmas Hulbert and Walters, Ltd. (the name was later changed to Christmas and Walters, Ltd.) in London. He held the agencies of the R. D. Wood Co. of Pittsburgh, the Chowning Regulator Corporation of Corning, New York, and the Blaw Knox Co. of Pittsburgh. He was Managing Director of the firm from its formation until the time of his death.

Mr. Christmas had been a Member of The Iron and Steel Institute for over 40 years, and was at one time a member of the Institution of Mechanical Engineers.

Sir Robert Crichton, C.B.E. died suddenly on 8th May, 1950, at the age of 69. He started work at the Victoria Works, Coatbridge, in 1898. In 1902 he gained the Associateship in Metallurgy from the Royal Technical College, Glasgow, and was awarded the B.Sc. degree in Engineering Science from Glasgow University in 1903. Sir Robert became Director of the Victoria Iron and Steel Co., Ltd., Coatbridge, in 1908, and in 1913 was appointed Director of the Scottish Iron and Steel Corporation, Glasgow, and later Vice-Chairman. In 1929 he went to Cumberland as Director and General Manager of The United Steel Companies' property in that county, a post which he held until 1937. From 1940 until the time of his death, Sir Robert was Vice-Chairman of the Lancashire Steel Corporation, Ltd., Warrington.

Among other industrial appointments that he held were those of Director of Ryland Bros. Ltd., Chairman of the Scottish Manufactured Iron Trade Conciliation and Arbitration Board, Chairman of the Scottish Bar Iron Association, and Director of the Wigan Coa Corporation. He was also Chairman of the West Cumberland Industrial Development Co., Ltd. from its inception until the time of his death.

Sir Robert was awarded the C.B.E. in 1939, and a knighthood was conferred on him in June, 1948. He was elected a Member of The Iron and Steel Institute in 1907 and from 1928–29 was President of the West of Scotland Iron and Steel Institute.

Hugo A. Dickie, D.Sc., Ph.D., F.I.M., A.R.T.C., died on 2nd May, 1950. He was educated at Glasgow University and at the Royal Technical College, Glasgow, and served his apprenticeship in a Clyde shipyard. After serving in the first World War he studied metallurgy and graduated B.Sc. in 1923; two years later he received the A.R.T.C. He was then awarded a Carnegie Research Scholarship and a Fellowship of the Carnegie Trust for the University of Scotland. He received the Ph.D. degree in 1927 and the D.Sc. in 1930.

Dr. Dickie joined the research department of Messrs. Stewarts and Lloyds, Ltd., in 1930, and was successively in charge of metallurgical, chemical, and general research, and at the time of his death was General Manager of Research.

He joined The Iron and Steel Institute in 1923. He was a Fellow of the Institution of Metallurgists, and a Member of the Institute of Metals. Dr. Dickie served on a number of technical committees of the British Iron and Steel Federation, the British Standards Institution, and the British Iron and Steel Research Association, and had made many contributions to the technical literature of the iron and steel industry, particularly on the metallurgy of steel.

Hywel Hopkins died on 12th March, 1950, in the Llandow air disaster. He was born at Aberavon, Port Talbot, in 1907, and was educated at the Port Talbot County School and at the Municipal Technical College, Swansea, where he passed the Final Examination of the City and Guilds Institute in the manufacture of iron and steel.

He started work in the laboratory of the Margam Iron and Steel Works of Messrs. Baldwins (now owned by the Steel Company of Wales) and at the time of his death was sample passer in the steel smelting shop.

Mr. Hopkins had been a member of the Swansea and District Metallurgical Society for 25 years and was elected a Member of The Iron and Steel Institute in 1946.

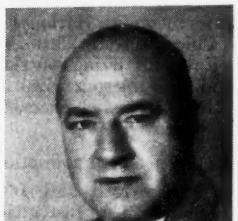
William G. Hutton died on 25th February, 1950, after a short illness. He was born in March 1895, and spent his whole life in the steel trade. At the age of 14 he started work at the Dalzell Works of David Colville and Sons, Ltd. Six years later, when Messrs. Colvilles took over the Clydebridge Steel Co., Ltd., he was transferred to Clydebridge as a chemist.

Mr. Hutton worked his way up to Chief Chemist, and in November 1942 became Assistant Melting-Shop Manager, the post which he held at the time of his death. He became a Member of The Iron and Steel Institute in 1940.

Stanley A. Jackson, General Manager of Messrs. Samuel Fox and Co., Ltd., died on 30th April, 1950. He was born in 1896, and at the age of 16 joined Messrs. Thos. Firth and Son, Ltd., as an apprentice. He worked in the laboratories, the casting pits, and on Siemens open-hearth and electric furnaces, and finally became shift manager in the melting shops.

Mr. Jackson went to India and later to Spain where he was Melting-Shop Manager and finally Works Manager of the Sociedad Española Construccion Naval Works at Reinosa. In 1933 Mr. Jackson returned to England as Works Manager of the Heavy Department of Samuel Fox and Co., Ltd., Stocksbridge Works. He held the positions of Director, General Works Manager, Assistant General Manager, and in 1944 was appointed General Manager, the post which he held at the time of his death.

Mr. Jackson's sound judgment, practical experience, and wide knowledge of industrial affairs enabled him to play a leading part in the development of one of the main centres of alloy and stainless steel production in this country. He was elected a Member of The Iron and Steel Institute in 1921.



S. A. Jackson

E. B. Muscroft died on 20th February, 1950. He was born in Sheffield on 5th July, 1886, and commenced work with Thomas W. Ward, Ltd. in a junior position in May, 1900. He specialized in the handling of scrap iron and steel and in 1923 was appointed Commercial Manager for the same firm, in the South Wales area.

From 1937 up to the time of his death, Mr. Muscroft was Liaison Officer to The British Iron and Steel Corporation Ltd., for the control of supplies of scrap iron and steel to the industry. In this way he has played a prominent part in the recovery of scrap, which has enabled the steel industry to reach record ingot steel production.

He became a Member of The Iron and Steel Institute in 1938.

Archibald P. Newall was born on 29th September, 1880, and at the age of 21 founded a limited company, bearing his name, which specialized in the production of high quality bolts and nuts. The Company was the first in this country, if not in the world, to produce bolts suitable for heat-treatment by the cold-heading process. The trade marks, "Newall Hitensile," "Newalloy," "Newallastic," and "Newall Hi-Tem" were all introduced by Mr. Newall. In latter years, due to illness, all his work was done over a private line between the Works and his home—40 miles away. Despite this handicap, the factory now covers a large area and is equipped with the most up-to-date machinery.

In bolt-manufacturing circles, Mr. Newall was acknowledged as a pioneer in the making of heat-treated bolts, and in 1945 he was presented with an illuminated memorial by the various bolt-manufacturing Associations in recognition of his contribution to the industry.

Mr. Newall joined The Iron and Steel Institute in 1917. He was also a Member of the Institution of Mechanical Engineers, the Institution of Engineers and Shipbuilders in Scotland, the Institute of Metals, and the British Standards Institution. For many years, he had been a member of the American Society for Metals, and The Wire Association.

Mr. Newall died at Perryston, Ayrshire, on 18th February, 1950.

Henrik Rudolf Sunstrom died on the 21st November, 1949. He was born in the U.S.A. in 1884 and educated in Sweden at the Technical Institute of Norrkoping, where in 1902 he graduated as a chemical engineer. Three years later he graduated as Master of Engineering, from Chalmer's Institute of Technology.

After one year at the Bongbro rolling mills in Sweden, he returned to the U.S.A. and was employed by various steel companies. In 1911 he joined the Gunnebo Bruks Aktiebolag in Sweden and from 1916–17 erected their first subsidiary factory at Varberg and became head engineer and superintendent of the factory. In 1922 he was appointed managing director of the Gunnebo Bruks AB, a post which he held until his retirement in 1949.

He was then elected Chairman of the board of the Company on which he had served since 1931. From 1933–39 he was also Chairman of the AB Slipmaterial-Naxos.

Mr. Sunstrom became a Member of The Iron and Steel Institute in 1927. He was also a Member of the Verein Deutscher Eisenhüttenleute and of some Swedish technical societies. In 1936 he was appointed a knight of the Vasa Order, and received the gold medal of the Royal Patriotic Society in 1939.

Rowland Village died on 25th March, 1950. He was born in Sheffield in 1887. In 1900 he started work in the office of Messrs. Jones and Colver, Ltd., and continued his metallurgical training at Sheffield University.

He subsequently became Siemens Department Manager with the same firm. He held similar positions with other steelworks—Cammell Laird and Co., Ltd., Pennistone, Andrews Toledo, Ltd., Sheffield, and Darlington Forde, Ltd. In 1939 he was appointed Works Manager at the Low Moor Alloy Steelworks Ltd., Bradford.

Two years later he started business on his own account and formed the Alloy Steel and Iron Company. The Company, which is being carried on by his five sons, now has two foundries, one at Chesterfield and one at Sheffield.

Mr. Village became a Member of The Iron and Steel Institute in 1936, and for many years was secretary of the Sheffield Branch of the Institute of British Foundrymen.

Albert Wright, of Scarborough, died on 11th January, 1950. At the age of 12, he started work with the North Eastern Steel Company, Middlesbrough, where he stayed for 18 years. In 1921, after working at various steelworks, he joined the Bilston Branch of Messrs. Stewarts and Lloyds, Ltd., as Manager of the rolling mills. He was appointed Steelworks Manager in 1925, and General Works Manager in 1932. He held this position until his retirement in 1943.

Mr. Wright was elected a Member of The Iron and Steel Institute in 1911. He had been a member of the Cleveland Institution of Engineers, a Vice-President of No. 3 Division of the Iron and Steel Employers' Association, and had served on committees of the British Standards Institution. He was a Past-President of the Staffordshire Iron and Steel Institute.

NEWS OF SCIENCE IN INDUSTRY

East Midlands Metallurgical Society

The East Midlands Metallurgical Society was recently inaugurated during a meeting at Nottingham and District Technical College. The Society has been formed to provide lectures, visits, discussions, and an annual dinner, in all the main towns and cities in the East Midlands Area in rotation. The Officers and Committee are :

President

C. H. BULLEID, O.B.E., M.A., A.M.I.C.E., M.I.Mech.E.

Vice-President	Hon. Treasurer
T. PARRY, F.I.M.	R. BINGHAM, L.I.M.

Committee

L. H. BAXTER, B.Sc.(Met.), A.I.M. (Grantham)	R. V. RILEY, Ph.D., A.I.M. (Chesterfield)
J. DEARDEN, M.Sc., F.I.M. (Derby)	J. I. WILLIAMS, B.Sc., A.R.I.C., A.I.M. (Loughborough)

Hon. Secretary

J. W. GAILER, M.Sc., F.R.I.C., A.I.M.

Institution of Mining and Metallurgy

The Gold Medal of the Institution of Mining and Metallurgy has been awarded to Mr. Robert Annan, E.M., M.I.M.M., Past-President of the Institution and Chairman of New Consolidated Gold Fields, Ltd., in recognition of his distinguished services to the mining industry and the mining profession.

Institution of Production Engineers

Mr. W. F. S. Woodford has been appointed Acting Secretary of the Institution of Production Engineers, following the resignation of the Secretary, Major C. B. Thorne, M.C.

Bicentenaries

M. AND W. GRAZEBROOK LTD. A luncheon at the Town Hall, Dudley, on 15th June, 1950, marked the bicentenary of the firm of M. and W. Grazebrook Ltd., heavy engineers and founders. Many prominent representatives of allied trades and associations were present. With family connections reaching back to 1615 the Company made its first entry to the iron industry during the life of Michael Grazebrook III (1723–1766). An important ceremony during the luncheon was the presentation by Mr. Owen Grazebrook, Chairman of the Company, to the City of Birmingham of a Boulton-Watt steam-driven blowing engine, installed by the Company in 1817.

HARRISON AND SONS LTD. The bicentenary of Harrison and Sons Ltd., printers of the *Journal*, was celebrated with a dinner at the Savoy Hotel on 7th June, 1950. Host to the many distinguished guests was Mr. Guy Harrison, present Chairman of the Company, whose great-great-grandfather was one of the founders. His young grandson was also present among others of the Harrison family.

Summer School in Automatic Computing, 1950

A Summer School in programme design for automatic digital computing machines is to be held from 12th to 21st September, 1950, in the Mathematical Laboratory of the University of Cambridge.

The course will give a basic training in the mathematical use of machines, dealing with the processes employed and their embodiment in programmes which specify the operations in detail. Lectures and practical classes will be held in the design of programmes for the EDSAC, the machine which has been built at the Laboratory. It will be shown how the same principles may be applied in designing programmes for other machines.

Associazione Italiana di Metallurgia

The Fourth National Congress of the Association will be held at Florence, Italy, from 28th September to 1st October, 1950. The programme includes discussion on papers on "Pure Metals" and "Metallurgical and Engineering Aspects of Machining." The complete programme will be published in due course in "La Metallurgia Italiana."

The Piedmontese Section of the Association has founded the Luigi Losana Foundation to honour the memory of Luigi Losana, researcher, educator, and technician. The aim of the Foundation is to promote, by the award of a medal, or by other means, the study of those subjects beloved by Professor Losana.

Metallographic Exhibit

The American Society for Metals has arranged for the Fifth Annual Metallographic Exhibit to be held at its forthcoming National Metal Congress and Exposition in Chicago, from 23rd–27th October, 1950.

Entrants living outside the U.S.A. are advised to send their micrographs by first-class letter mail, endorsed "May be opened for customs inspection before delivery to addressee."

Conference on Production

On the 15th and 16th November, the Utilization Section of The Institution of Electrical Engineers are holding a Conference on "Electricity as an Aid to Productivity" in order to make available to industry the most up-to-date information concerning the contribution that factory electrification can make to the country's efforts towards increased production.

The Conference is mainly intended for those executives in both large and small factories who are responsible for production, and will consist of a series of lectures each of which will be followed by a general discussion.

The subject matter of the lectures will come under the following broad headings: (*a*) Motive power in the factory, (*b*) Industrial heating processes, (*c*) Welding applications, (*d*) The handling and inspection of materials, and (*e*) Lighting, heating, ventilation, etc.

The proceedings of the Conference will be published and issued to all interested parties so as to reach as wide an audience as possible.

Welding Research

The Council of the British Welding Research Association gratefully accepted an offer from the British Oxygen Co., Ltd., in 1948, to provide a prize fund for three years for a competition relating to welding.

The first competition was held during 1948/49 when no award was made. The result for 1949/50 has not yet been decided. During 1950/51 a single prize of £100 will be awarded for the best paper submitted on a research into welding or its applications. A copy of the regulations for the award may be obtained from the Association at 29 Park Crescent, London, W.1.

Changes of Address and Title

BRITISH ASSOCIATION FOR COMMERCIAL AND INDUSTRIAL EDUCATION (BACIE) have removed their London office from 174 Sloane Street, to Management House, Hill Street, London, W.1. Telephone No. Grosvenor 6231/2.

DEPARTMENT OF SCIENTIFIC AND INDUSTRIAL RESEARCH have removed from Rex House, to Charles House, 5–11 Regent Street, London, S.W.1. The telephone number remains Whitehall 9788.

THE MECHANICAL ENGINEERING RESEARCH ORGANIZATION has transferred to Thorntonhall, Glasgow. Telephone No. Busby 1171.

THE SHEEPBRIDGE STOKES CENTRIFUGAL CASTINGS CO., LTD., of Chesterfield and Sutton-in-Ashfield, will in future be known as Sheepbridge Stokes, Ltd.

Industrial Publications

▶ Thomas Marshall and Co., (Loxley) Ltd., have published a brochure illustrating and describing the refractory products of the Company and its associates. Prominence is given to casting-pit and furnace-lining refractories.

▶ The Woodall-Duckham Vertical Retort and Oven Construction Co., Ltd., have prepared an illustrated description of the new coke-oven plant installed at the Fell Works of the Consett Iron Co., Ltd., Co. Durham. The plant came into operation in May, 1948.

▶ Press Shop equipment, manufactured in England by Rockwell Machine Tool Co., Ltd., under licence and to the design of the U.S. Tool Co., Inc., U.S.A., is illustrated in a new catalogue issued by the Company.

▶ The revised V.F.C. publication No. 59 of Birlec Limited describes and illustrates the Company's range of forced air circulation furnaces, which are suitable for low-temperature (up to 700° C.) heat-treatment. A separate catalogue illustrates large horizontal and vertical batch furnaces, suitable for most metallurgical heating processes.

▶ To commemorate their twenty-fifth anniversary, Croda Limited, manufacturers of wool grease products, have prepared a booklet describing the rapid development of the Company, particularly in providing special oils and waxes during the war.

▶ Kent Multelec Recorders for the accurate measurement of electrolytic conductivity, are described, with technical details, in Publication No. 864/949 of George Kent, Ltd., Luton.

▶ A catalogue, which covers the full range of the revised standard cemented carbide tips and tools, has been issued by William Jessop and Sons Ltd., and J. J. Saville and Co., Ltd., Sheffield. Illustrations and lists of sizes and prices of the Cutanit series are given.

▶ The Mond Nickel Co., Ltd. have prepared a brochure giving technical details of castings in nickel–aluminium bronze to B.S. 1400-AB2-C. The information includes composition and properties, fabricating techniques, and founding practice.

DIARY

6th July–30th Sept.—INSTITUTION OF METALLURGISTS — Metallurgical Exhibition — Science Museum, London, S.W.7.

7th–18th Aug.—MASSACHUSETTS INSTITUTE OF TECHNOLOGY—Two-week Summer Programme in High Temperature Ceramics—Cambridge, Massachusetts.

7th–20th Aug.—UNITED STATES INTERNATIONAL TRADE FAIR—Chicago.

14th–20th Aug.—INTERNATIONAL UNION OF HISTORICAL SCIENCES—Sixth International Congress—Amsterdam University.

30th Aug.–3rd Sept.—INSTITUTION OF PRODUCTION ENGINEERS—1st Annual Summer School—St. Peter's Hall, Oxford.

30th Aug.–6th Sept.—BRITISH ASSOCIATION FOR THE ADVANCEMENT OF SCIENCE—Annual Meeting—Birmingham.

30th Aug.–7th Sept.—INDUSTRIAL FINISHES EXHIBITION—Earls Court, London, S.W.5.

TRANSLATION SERVICE

(The previous announcement was made in the July, 1950, issue of the *Journal*, p. 344).

TRANSLATIONS AVAILABLE

No. 401 (German). F. KELLER: "Investigation of the Power Required for Cutting by Shearing along a Straight Line." (*Werkstatt und Betrieb*, 1949, vol. 82, May, pp. 165–171).

No. 402 (German). G. GILLE and J. WILLEMS: "Temperature and Flame Measurement in the Bessemer Process." (*Stahl und Eisen*, 1949, vol. 69, Oct. 27, pp. 759–762).

No. 403 (German). J. WILLEMS, G. GILLE, and H. HÖFGES: "Observations on the Course of the Reaction towards the End of the Bessemer Blow with the Aid of Temperature and Flame Measurements." (*Stahl und Eisen*, 1949, vol. 69, Oct. 27, pp. 762–764).

TRANSLATION IN COURSE OF PREPARATION

(Czech). F. SICHA: "The Influence of the Chemical Composition of Hypo-Eutectoid Steels on the Ac_3 Temperature and the Optimum Hardening Temperature." (Hutnické Listy, 1949, vol. 4, June, pp. 169–174).

CHARGES FOR COPIES OF TRANSLATIONS—The charge for the above translations is £1 for the first copy and 10*s*. for each additional copy of the same translation. Requests should be accompanied by a remittance. These translations are not available on loan from the Joint Library.

TRANSLATIONS PREPARED AT MEMBERS' REQUEST—Members requiring translations of foreign papers are invited to communicate with the Secretary, who will ascertain whether they can be prepared for inclusion in the Series.

ABSTRACTS OF CURRENT LITERATURE *and* BOOK NOTICES

IRON AND STEEL MANUFACTURE AND RELATED SUBJECTS

CONTENTS

	PAGE
ORES—MINING AND TREATMENT	462
FUEL—PREPARATION, PROPERTIES, AND USES	463
REFRACTORY MATERIALS	463
BLAST-FURNACE PRACTICE AND PRODUCTION OF PIG IRON	464
PRODUCTION OF STEEL	464
FOUNDRY PRACTICE	465
HEATING FURNACES AND SOAKING PITS	465
FORGING, STAMPING, DRAWING, AND PRESSING ...	465
ROLLING-MILL PRACTICE	465
MACHINERY FOR IRON AND STEEL PLANT	466
PROPERTIES AND TESTS	466
METALLOGRAPHY	468
CORROSION	469
ANALYSIS	470
BOOK NOTICES	470
NEW PUBLICATIONS	472

ORES—MINING AND TREATMENT

The Explosive Effect of Externally Placed Charges on Blocks and Boulders. G. Fagerberg and C. H. Johansson. (Jernkontorets Annaler, 1949, vol. 133, No. 6, pp. 199–232). [In Swedish]. The possibilities of using directional blasting in iron ore mines have been examined. The trials described have shown that external charges in cavities with metal liners are unsuitable for use in place of shot-firing in drilled holes. Compact and hollow explosives have also been tested on concrete blocks and boulders and the consumption to produce specific effects has been recorded; the cost was excessive, but this technique had the advantage that the fragments were not scattered very much.—R. A. R.

Rock-Drilling with Tungsten-Carbide-Tipped Bits. T. Ekstam, K. H. Fraenkel, and E. Ryd. (Jernkontorets Annaler, 1949, vol. 133, No. 8, pp. 253–299). [In Swedish]. This report covers a discussion arranged by the Mining Research Committee of Jernkontoret on the use of tungsten-carbide-tipped bits for rock drilling. This hard-metal drilling has been most successful in development work, but it has only been introduced slowly in Sweden. A procedure for gathering statistics on the life of the steels and bits and the reasons for discarding broken ones is now in operation and is used as a basis for the improvement of bits. A standard drilling machine has been applied to determine the drilling resistances of different kinds of rock and from the data obtained, methods, times, and costs, including the consumption of compressed air and spares, have been calculated. The effect of the size of the drill on the durability of the bit is examined and the advantages of a light-weight easily moved drilling machine are pointed out. Specimens of the report forms used to collect statistics are reproduced.—R. A. R.

Fine-Screening Investigations. Part III. B. Fagerberg and S. Mörtsell. (Jernkontorets Annaler, 1949, vol. 133, No. 4, pp. 125–152). [In Swedish]. Investigations on the screening of magnetite concentrates have been continued (for Part II *see* Journ. I. and S.I., 1949, vol. 161, Apr., p. 372). In this paper a comparison is made of the screening properties of drums and Traylor screens when screening magnetite concentrates using meshes in the 0·15 to 0·50-mm. range. Heavy concentrates of round uniform grains are better and more rapidly screened than light angular ones. If flat particles, *e.g.*, mica, are present, screening is more difficult.—R. A. R.

Determination of the Specific Surface of Finely Divided Materials by the Gas Permeability Method. J. Svensson. (Jernkontorets Annaler, 1949, vol. 133, No. 2, pp. 33–86). [In Swedish]. An investigation of the permeability method of determining the specific surface of finely divided materials is reported; the work is part of Jernkontoret's research work on crushing and grinding. The theory is dealt with at length and a general expression for the permeability of a bed is developed.

Two different experimental arrangements were used, one, a fairly conventional apparatus where the flowing medium was air at atmospheric pressure, and the second, a completely closed apparatus in which the permeability was determined with air as well as with nitrogen at pressures between 1 and 76 cm. Hg. In the second apparatus the permeability of the bed investigated was compared with that of a bed of glass beads. Nineteen experiments were made on finely divided quartz and a great number of surface determinations were made on sized material, ground products, and mixtures of ground products.—R. A. R.

Dephosphorization of Iron Ore. C. G. Granström. (Jernkontorets Annaler, 1949, vol. 133, No. 9, pp. 323–370). [In Swedish]. The problem of leaching iron ores with acid to remove the phosphorus is dealt with by reporting the results of laboratory-scale and pilot-plant tests in Sweden; a brief description of the new plant at Grängesberg for treating 30,000 tons of ore per annum is also given.

The results of laboratory tests by C. C. Breitholtz with black ore and hematite concentrates leached with nitric acid can be summarized as follows: (1) The feed must be highly concentrated to lower the phosphorus so that the acid consumption will not be too high. (2) The feed must be effectively dewatered so that the acid concentration will remain high. (3) The consumption of concentrated HNO_3 (96%) was about 12 kg./1000 kg. ore for each 0·1% phosphorus removed. (4) The leaching time must be at least 1 hr. (5) The leaching time can be reduced by raising the temperature of the ore to about 50° C. The reaction between the acid and ore itself raises the temperature to about 25° C. without any insulating material on the outside of the leaching vessel.

The Research Committee of Jernkontoret in 1945 established that highly concentrated Malmberg and Grängesberg ores could be produced containing 0·010% phosphorus and acid-leaching must be applied to get the phosphorus still lower; also that laboratory tests, and others with 1-ton charges, had lowered the phosphorus content as far as 0·003%, whilst tests with a continuous process using HCl were unsuccessful.

Tests using 5-kg. samples of magnetite concentrate (Fe 71·8%, P 0·066%) and of hematite concentrate (Fe 69·1%, P 0·114%) using 96% HNO_3, 96% H_2SO_4, 38% HCl, and 100% H_3PO_4 showed that a mixture of HNO_3 and HCl had a high leaching capacity for phosphorus, but it also dissolved a good deal of iron from both the concentrate and the walls of

the leaching vessel. HNO_3, and to some extent mixtures of HNO_3 and H_2SO_4, leached uniformly and most efficiently; both acids are concentrated and easy to transport and store. With H_2SO_4 some gypsum was formed, but it was so fine that it was easily removed in the washing process.

In 1948 4417 metric tons of concentrate (P 0·080%) were leached in the Grängesberg pilot plant producing 1·135 metric tons/hr. concentrate (P 0·008%) with a consumption of 18·01 kg. of 96% HNO_3 per ton.

At the new full-scale plant at Grängesberg, concentrate is fed from two 700-ton concrete bunkers into rotary leaching chambers 2050 mm. inside dia. × 3250 mm. long of welded 10-mm. thick stainless steel fitted internally with eight longitudinal and eight oblique blades 100 mm. deep. This is rotated at 10–20 r.p.m. depending on the leaching time. Acid is fed in from an 18-cu. m. aluminium storage tank, the quantity being controlled by an intermediate vessel with two compartments separated by a perforated plate calibrated for different quantities. The calculated capacity of the leaching vessels is 2·3 cu. m. each, equivalent to about 10 tons of ore and acid; the throughput is about 3¾–4 metric tons/hr. The product is dewatered in vertical cylinders 1 m. × 1 m., with vertical paddles rotated at 350 r.p.m., into which water is fed at 600 l./min. The slime is pumped to a spets for dewatering and the thickened product goes to a shaker dewaterer and thence by conveyor belt to the storage place. The dewatered product contains about 8–9% of moisture.

The process, which is patented, is characterized by the fact that undiluted mineral acids are used, the total moisture content of the acid plus water is limited to 15% by weight. The concentrate is dewatered to the correct moisture content before dephosphorization; this ensures intimate contact between the acid and the concentrate particles whilst the high acid concentration is maintained.

This process is thus not an ordinary leaching, but is rather to be regarded as an extraction process—a point which is included in the patent claims. The principal advantages of the process are: (1) Highly concentrated acid (96%) can be used; (2) the products leached out are easily soluble and can readily be obtained by washing; (3) the products can be used for manures; and (4) there is no risk of the reprecipitation of phosphorus..—R. A. R.

FUEL—PREPARATION, PROPERTIES, AND USES

Special Burner Converts Gas Furnace for Oil. G. J. Gollin. (Iron Age, 1950, vol. 165, April 13, pp. 89–92). The **Y**-burner, of British design, and its applications for replacing gas-firing in muffles, annealing furnaces, ceramic tunnel kilns, etc., are described. It may be regulated from a consumption of 20 to 0–5 lb./hr. of oil, its dimensions are small enough for it to replace a gas burner, its internal passages are large enough to prevent clogging at a high degree of radiant heat, and the flame is small enough to be directed into existing primary combustion chambers designed for gas.—J. P. S.

Investigation of the Burner Coefficient ' k ' and Heat Flow in Fuel-Fired Furnaces. Part II. R. Dawidowski, W. Bilyk, and T. Senkara. (Prace Badawcze Glownego Instytutu Metalurgii i Odlewnictwa, 1949, No. 2, pp. 127–130). [In Polish]. The burner coefficient and the coefficient of heat transfer have been determined for the Meyerhold burner size No. 3.—W. J. W.

Dense-Media Washing of Coal with Special Reference to the Chance Process. F. C. Meyer. (Journal of the South African Institution of Engineers, 1949, vol. 48, Dec., pp. 106–131).

British Use High Wall Coke Ovens. D. Bagley. (Iron Age, 1950, vol. 165, Mar. 2, pp. 95–96). Differences between British and American coking practice are described; the former usually employs Still-type ovens which are higher than those of the Koppers and Wilputte types employed by the latter. The method of firing is also different. These differences arise because, whereas American practice is based on the use of coal blended from low and high volatile materials, British operators still use high volatile coal. Difficulties experienced by American operators in uniformly heating high-wall ovens have been overcome in the Still-type oven, where variation of wall temperature in any direction is less than 30° C. The side-jet firing of the Still oven is described and illustrated and it is explained that by forcing this, the coking period could be reduced from 20 to 16 hr., the regular American period; on the 20-hr. period, however, ovens of this type are already coking 37 tons/24 hr. against 20–24 tons/24 hr. in the United States, so that the advantages of the high-wall oven would be still further increased.—J. P. S.

The Drum Test and the Modern View on the Quality of Blast-Furnace Coke. T. Kozlowski and J. Nadziakiewicz. (Hutnik, 1949, vol. 16, July–Aug., pp. 297–310). [In Polish]. The present methods of testing the coke for blast-furnaces are reviewed and their shortcomings are discussed. Many examples are described, based mainly on data of Russian coke production, in which the behaviour of coke in the blast-furnace itself is studied.—W. J. W.

REFRACTORY MATERIALS

Better Mold Liners for Dry Pressing Brick. R. D. Haworth. (Iron Age, 1950, vol. 165, Feb. 9, pp. 79–83). Mould wear in the dry-pressing of refractory bricks, of silica, chromite, magnesite, etc., is often severe. By means of an abrasion tester consisting of a rubber wheel running in a suspension of the raw material of the brick, the abrasion resistance of various materials has been tested. Various factors affect this, including the speed and pressure of the wheel and the grain-size of the abrasive. High-chromium high-carbon steel, and a modified high-speed steel are the most satisfactory materials. Correlation between results found in practice and the results of the higher-speed laboratory tests is not good, but between lower-speed, higher-pressure tests, and field tests, correlation is far better. Further studies, notably of the effect of heat-treatment, are in progress.—J. P. S.

Ceramic Raw Materials of Poland. L. Tokarski. (Przeglad Techniczny, 1949, May–June, pp. 153–158). [In Polish]. The distribution of ceramic raw materials in Poland is described, and the usefulness of dolomite, magnesite, quartz, and kaolin for refractory materials is dealt with.—W. J. W.

X-Ray Investigations on Polymorphic Transformations in Polish Silica Raw Materials. Z. Bojarski. (Prace Badawcze Glownego Instytutu Metalurgii i Odlewnictwa, 1949, No. 2, pp. 183–187). [In Polish]. X-ray diffraction technique has been applied to the determination of polymorphic transformations in Polish raw materials used in the refractory industries. The degree of transformation was determined by comparing the patterns with those of a mixture of quartz and cristobalite.—W. J. W.

Investigations on Crushed Quartz from Rådanefors. F. Sandford. (Jernkontorets Annaler, 1949, vol. 133, No. 3, pp. 99–124). [In Swedish]. The paper reports investigations on the relation between the grain-size distribution and some properties of quartz from Rådanefors when used in acid open-hearth furnaces and moulds for steel castings.—R. A. R.

Refractory Constructional Materials in the Metallurgical Industry. H. van Thiel. (Die Technik, 1949, vol. 4, Dec., pp. 574–577). The German Engineering Standards for refractory materials do not by any means cover all the requirements for refractories in the iron and steel industry. The author here discusses some of the aspects not covered by the Standards, *i.e.*, resistance to slag, resistance to decomposition by carbon, magnesite bricks, chrome-magnesite bricks, ramming materials, and carbon linings for blast-furnaces.—R. A. R.

News Gleanings for the Refractories Industry. L. Sanderson. (Refractories Journal, 1949, vol. 25, Aug., pp. 278–281). Among the items mentioned in this survey are: (1) A new mineral, known as Refrasil, developed primarily for insulating parts of jet engines, is said to withstand a sustained temperature of 2000° F.; (2) ceramic pots for hardening high-speed steel; (3) applying thin patches of moisture-controlled ganister and clay, rammed to maximum density, to holes in cupola linings without attempting to restore the original shape of the lining; and (4) water-cooled bosh linings to cupolas.—R. A. R.

Refractories—Their Selection and Specification. B. L. Majumder and M. A. Ghani. (Refractories Journal, 1949, vol. 25, Aug., pp. 265–273). The difficulty of drawing up specifications for refractory materials is explained, and the following properties and conditions which must be taken into account when purchasing refractories are discussed: (1) Highest temperature to which the refractory will be exposed in use; (2) conditions of atmosphere in the kiln; (3) effect of flame and flue dust; (4) pressure exerted by the adjacent masonry and material in the furnace; (5) effect of sudden and repeated changes in temperature; (6) slag attack whilst

in contact with fluid slags, glasses, or flue dust ; (7) thermal properties of the refractory material ; (8) volume stability ; (9) texture ; (10) type of fuel ; and (11) cost and quality.—R. A. R.

BLAST-FURNACE PRACTICE AND PRODUCTION OF PIG IRON

On the Diameter and Number of Tuyeres in the Blast-Furnace. W. Kuczewski. (Hutnik, 1949, July–Aug., vol. 16, pp. 311–314). [In Polish]. Calculations are presented on the diameter and number of tuyeres in the blast-furnace based on examples from nine blast-furnaces of which three are American and six Russian. A blast-furnace with 12 tuyeres 225 mm. in dia. is regarded as having the optimum efficiency.—W. J. W.

The 'Variable Turbulence' Stove and the Denain Trials. Part III. D. Petit. (Instituto del Hierro y del Acero, 1949, vol. 2, Oct.–Dec., pp. 36–43). [In Spanish]. Continuation of a paper (*see* Journ. I. and S.I., 1950, vol. 164, Apr., p. 485). In this part the author discusses the variation of heat capacity as a function of blast temperature, the calculation of the optimum duration of reversals, the question of stove dimensions, and combustion losses. The disadvantages of stoves with smooth walls, zones, constant turbulence, and transverse circulation, are outlined. Results of the Denain trials showed the advantages of 'variable turbulence' stoves as regards flexibility and economy. A most important factor is the availability of considerable reserves of heat. Finally, the work at Denain has provided a basis for the precise calculations of the dimensions and characteristics of any given stove and for the determination of the yield under different working conditions.—R. S.

Developments in Blast-Furnace Efficiency. T. P. Colclough. (International Foundry Congress 1949 : Metalen, 1950 Congress Number, Part I, pp. 14–30). After reviewing developments tending to increase blast-furnace efficiency, the author shows that proper burden distribution and composition are of the highest importance, and to achieve this, ore-preparation plants are essential. For economic reasons, a large throughput of ore and therefore a concentration of pig-iron manufacture are necessary. The present trend is to replace obsolete blast-furnaces with new ones having a hearth diameter of 18 to 20 ft. and a capacity of 2500 to 3000 tons of pig iron on lean ore burdens, or 5000 tons/week on rich ores. Except for special local conditions, the use of small blast-furnaces to produce foundry iron in scattered plants is rapidly coming to an end.—R. A. R.

Recent Progress in Blast Furnace Practice. G. Grenier. (Documentation Métallurgique, 1949, Apr.–June, pp. 35–45 ; July–Sept., pp. 71–81 ; Oct.–Dec., pp. 107–117). Modern developments in blast-furnace practice are reviewed with special reference to acid practice, use of carbonate of soda for desulphurization, preparation of the charge, use of oxygen-enriched air and high top pressures, the Tysland-Hole furnace, and the accumulation of heat in Cowper stoves.—R. F. F.

PRODUCTION OF STEEL

The Effect of Manganese on the Metallurgical Reactions in the Basic Open-Hearth Process. S. Fornander. (Jernkontorets Annaler, 1949, vol. 133, No. 5, pp. 163–190). [In Swedish]. Thirty-six experimental heats were made at four different works to study the effect of the manganese content of the charge on the reactions in the basic open-hearth furnace. A new method was developed for taking bath samples for determining the oxygen content. The manganese in the charge, which was varied between 0·15 and 2·3%, had no influence on the oxygen content of the bath or on the rate of carbon drop. The oxygen content of the steel increases linearly with time towards the end of the heat, and there seems to be a linear relationship between the rate of oxygen increase and the rate of carbon drop at lower carbon contents. The MgO in the slag decreased with increasing manganese in the charge.—R. A. R.

Slag Control in the Basic Open-Hearth Furnace Process. Part II. A. Ludkiewicz, E. Bucko, and J. Zieba. (Prace Badawcze Glownego Instytutu Metalurgii i Odlewnictwa, 1949, No. 2, pp. 155–161). [In Polish]. Further examination of slag in the basic open-hearth furnace has been carried out so as to complete the series previously established. The evaluation of slag basicity has been carried out by examining the top and bottom surfaces of slag pancakes, and the results are compared with those calculated on the basis of chemical analysis. Accuracy of the determination of slag basicity, inferred from physical properties of slag pancakes, is satisfactory up to basicity $V = 3 \cdot 0$ and is adequate for practical requirements. The examination of thin sections of slag with polarized light revealed three types of slag, each of them characterized by a typical phase. Microscopical examination proved useful for the control of slag basicity.—W. J. W.

Thermodynamic Aspects of the Movement of Sulphur between Gas and Slag in the Basic Open-Hearth Process. F. D. Richardson and G. Withers. (Journal of The Iron and Steel Institute, 1950, vol. 165, May, pp. 66–71). A theoretical study is made of the sulphur equilibrium between a basic slag containing sulphur and the furnace gases in the open-hearth process. It is concluded that the higher the slag temperature and the more complete the degree of combustion of the gases coming into contact with the slag surface, the less chance there is of the slag picking up sulphur from the gas phase. The combustion limits which are required at the slag surface in the presence of gases of various sulphur contents, to avoid pick-up in the refining period, have been calculated. It is suggested that if these limits can be exceeded in practice, it should be possible to pass sulphur from metal to gas *via* the slag at the same time as oxygen is passed from gas to metal.

Present State of the Ugine Perrin Processes of 'Rapid Metallurgy.' A. Portevin. (Instituto del Hierro y del Acero, 1949, vol. 2, Oct.–Dec., pp. 6–15). [In Spanish]. The tendency to produce economically high-grade products from low-grade raw materials has resulted largely from the processes of 'rapid metallurgy.' These processes are based on three principles : (1) Rapidity, and the replacement of the slow action of a slag on a metal in a large furnace by the almost instantaneous action of the metal on a molten slag in a ladle ; (2) automatic reproducibility and uniformity, independent of the human factor (this has now been achieved by temperature control) ; and (3) independence of the final result of such factors as the nature of the furnace in which the steel has been made.

These general principles have been applied in three directions : (*a*) dephosphorization ; (*b*) simultaneous deoxidation and desulphurization ; and (*c*) the manufacture of certain ferro-alloys. These three aspects are briefly reviewed.—R. S.

Scrap Preparation. R. F. Fien. (Iron and Steel Engineer, 1949, vol. 26, Nov., pp. 86–88). A description is given of the methods adopted at the Dearborn works of the Ford Motor Co. for classifying scrap, bundling it, and transporting it to the furnaces. The importance of baling scrap and cutting large scrap to increase the weight per buggy and to reduce charging time, is emphasized.—J. C. R.

Corrigenda

In the abstract entitled "Desulphurization in the Basic Open Hearth Furnace Using Bauxite" (April *Journal*, p. 486, col. 2) it was stated that the Volta Redonda plant used charges with a high proportion of cold scrap ; this should read "a high proportion of cold pig iron."

In the abstract entitled "Spectrographic Determination of Aluminium and Titanium in Steels" (May *Journal*, p. 125, col. 1) instead of "rotating spark gap" read "rotary interrupter."

In the February *Journal*, p. 236, col. 2, abstract 4, the author's name should be Z. Wusatowski.

Some Trends in Arc-Furnace Design. J. C. Howard. (Iron and Coal Trades Review, 1950, vol. 160, Jan. 20, pp. 131–134). Trends in modern electric furnaces are described, including types of circuit-breaker, power input, body design, and general layout.—J. C. R.

Deleterious Effects of Hydrogen in Electric Arc Furnace Steels. J. Almunia y de Leon. (Instituto del Hierro y del Acero, 1949, vol. 2, Oct.–Dec., pp. 79–82). [In Spanish]. On the basis of his personal experience, the author comments on the subject of the effects of hydrogen in steels made in the electric furnace, discussed by S. V. Simpkinson in his paper entitled "Melting of Quality Basic Electric Steel." He cites observations made in Spanish steelworks to corroborate certain points in Simkinson's work.—R. S.

FOUNDRY PRACTICE

Some Factors Influencing the Use of Ethyl Silicate in Precision Casting. H. G. Emblem, A. E. Meadowcroft, and G. E. Stockwell. (Metallurgia, 1950, vol. 41, Jan., pp. 157–159). Methods are described for determining the suitability of commercial ethyl silicate for bonding investments, and spray or dip coatings used in the lost-wax process of precision casting.—R. A. R.

Bimetallic Bonding Gives New Parts Design Possibilities. C. E. Stevens, jun. (SAE Journal, 1950, vol. 58, Jan., pp. 32–35). A casting process has been devised by which aluminium is bonded on to cast iron and some applications of bimetal castings are described. They include (*a*) a cast-iron insert bonded to an aluminium piston to carry the upper piston rings; (*b*) aluminium–tin bearings backed with steel; and (*c*) a gear housing with a bonded steel bearing cage. R. A. R.

Drilling for Oil with Large Precision Castings. K. J. Yonker and J. F. Henderson. (Iron Age, 1950, vol. 165, Feb. 2, pp. 75–78). A 'turbo drill' designed to operate on the hydraulic pressure of the mud supplied to an oil drill and thus replace conventional drilling from the surface, contains a 90-stage turbine having 90 rotor discs and 91 stator discs, each having about 30 blades: the disc units were precision cast in an alloy of unstated composition. Intricate dies were necessary for the production of the wax patterns. The as-cast weight of the rotor is 8 lb. and that of the stator 12 lb.—J. P. S.

HEATING FURNACES AND SOAKING PITS

Production Line Heating for Forging. F. O. Hess. (Steel Processing, 1950, vol. 36, Jan., pp. 37–42). The advantages of high-speed radiant gas heating for forgings are discussed and some installations for the rapid heating of bars and tubes are described. The advantages include less scaling loss, better surface condition, and less decarburization.—R. A. R.

Fast Heating of Large Diameter Pipe. R. M. Hortvet. (Iron Age, 1950, vol. 165, Feb. 16, pp. 97–99). A furnace for reheating large diameter (up to 12¾ in.) pipe for reducing to smaller sizes is described. It is cylindrical in shape and gas-fired; the flames travel tangentially round the furnace wall and the work is heated by radiation. The pipes travel through at 20 ft./min. and, the furnace wall being maintained at 2000° F. (1090° C.), are heated to 1000° F. (538° C.) in about 70 sec.—J. P. S.

Heat Transfer. W. H. McAdams. (Chemical Engineering Progress, 1950, vol. 46, Mar., pp. 121–130). This paper reviews methods of calculating heat transfer for a great variety of conditions, and gives examples. There is a bibliography of 101 references.—R. A. R.

FORGING, STAMPING, DRAWING, AND PRESSING

A Review of the Forging Industry. H. L. Showalter, jun. (Steel Processing, 1950, vol. 36, Jan., pp. 26–30, 44). This review of the American forging industry indicates that great attention is being given to better accounting and estimating, and to improved maintenance.—R. A. R.

On the Design and Performance of Steam Hammers. E. Kiss. (Bányászati és Kohászati Lapok, 1949, vol. 4, Oct., pp. 433–439). [In Hungarian]. The design of steam hammers is carried out on the basis of the energy output of the hammer during a stroke. A method of determination of the impact energy, the number of blows per minute and the steam consumption of automatically controlled steam hammers is presented. The importance of correct rate of steam admission and the conditions of regulation are discussed. A numerical example is included to illustrate the basic principles of steam hammer design by the author's method. E. G.

Large Forgings. J. Novák. (Hutnické Listy, 1950, vol. 5, Jan., pp. 10–17). [In Czech]. The factors affecting the quality of large forgings are discussed and the author emphasizes the urgent necessity of revision of obsolete quality specifications. Such specifications may force the manufacturer to adopt excessively expensive forging processes which are technically unjustified. Several practical examples are enumerated which show that various tests did not give conclusive results. For instance, a chromium–nickel–molybdenum steel rotor had passed a rigid optical inspection of the axial bore. The forging remained unused for several years, and later, when it was to be used for another purpose, numerous fine corrosion cracks were revealed and the forging had to be scrapped. The author emphasizes the necessity for closer co-operation between the designer and the metallurgist. He expresses the view that large forgings are satisfactory in many cases, even if they contain some imperfections, provided that the usual safety factor is taken as a basis for calculations.—E. G.

Forgings for Marine Purposes. R. C. Benson. (ESC News, 1949, vol. 3, No. 3, pp. 3–8). The process of forging rudderstocks, one-piece rudder frames, and propeller shaft brackets at the works of Darlington Forge Ltd. is described and illustrated.—R. A. R.

ROLLING-MILL PRACTICE

The Building of Rolling Mills. M. A. Fiennes. (Institution of Production Engineers: Iron and Coal Trades Review, 1950, vol. 160, Feb. 17, pp. 361–370). An account is given of the building of rolling mills and the organization of a large heavy engineering works.—J. C. R.

Pressure, Elongation and Spread of Steel during Hot Rolling. Z. Wusatowski. (Hutnické Listy, 1949, vol. 4, Dec., pp. 406–412). [In Czech]. The influence of roll pressure, initial shape of the material, diameter of the rolls, composition of the rolled steel, rolling temperature and speed, and the friction between the rolls on the rolled material were investigated for mild carbon steels rolled at ordinary temperatures. The author uses his own and other authors' data as a basis for a mathematical analysis of the influence of the above factors on the deformation of steel during hot rolling.—E. G.

Modernization of the Steelton Blooming Mill. R. M. Weigle. (Iron and Steel Engineer, 1949, vol. 26, Nov., pp. 97–103). The 44-in. blooming mill at the Steelton plant of the Bethlehem Steel Co. has recently been modernized, and descriptions are given of the new equipment. This includes 16 top-fired, recuperative-type soaking pits, improved ingot-handling facilities, a new type of control in the field circuits of the blooming-mill motor and generator, and new main tables and feed rollers.—J. C. R.

A Four-High Reversing Cold Strip Mill. L. L. Wilson. (Iron and Steel Engineer, 1949, vol. 26, Nov., pp. 71–75). In this discussion on four-high reversing cold strip mills the author describes an experimental mill which had work rolls 3 in. in dia., back-up rolls 14 in. in dia., and a roll face of 10 in. Its purpose was to serve as a finishing mill for light-gauge hard material such as razor-blade steel, stainless steel, and silicon steel. Power was applied to the work rolls by driving the back-up rolls and by tension. A larger mill, to be used as an all-purpose mill for general production, is being designed and some of the factors that have to be considered are analysed. These include the size of the work rolls, the practical speed of operation, and bottom coiling. J. C. R.

Electrical Features of Four-High Reversing Cold Strip Mill. J. S. Apperson, jun. (Iron and Steel Engineer, 1949, vol. 26, Nov., pp. 76–80). The electrical equipment used on an existing 10-in. four-high reversing cold strip mill is described and an account is given of tests carried out with this mill. The data obtained are compared with test data on other cold mills and it is indicated how this information can be used to determine the power requirements of a proposed 28-in. mill. The electrical equipment that might be used on such a mill is described.—J. C. R.

D-C Drives on Runout Tables and Coilers. I. N. Tull. (Iron and Steel Engineer, 1949, vol. 26, Nov., pp. 53–59). An account is presented of 11 years' operational experience with D.C. mill motors on run-out tables used with the 98-in. hot strip mill at the Cleveland, Ohio, works of the Republic Steel Corporation. Some of the advantages gained by using D.C. instead of A.C. motors are discussed.—J. C. R.

Aspects of Portuguese National Industry. J. Sanz y Diaz. (Metalurgia y Electricidad, 1949, vol. 14, Dec., pp. 86–87). [In Spanish]. The Portuguese Metallurgical Company is building a tinplate mill near Oporto. Iron sheets will be imported for cold rolling and tinning.

Tungsten is being produced in electric furnaces.

Portuguese ores are believed to be sufficient to guarantee regular supplies to the Spanish metallurgical industry. One deposit at Moncorvo has a vein which is estimated at

160,000,000 tons of iron ore, apart from deposits at Marao, Cuadramil, and Orada, in the province of Alentejo. No further details of these resources are given.—R. S.

General Outline of Production of Light Shapes. M. Zdunkiewicz. (Przeglad Techniczny, 1949, May–June, pp. 159–163). [In Polish]. The rolling equipment and processes for producing intricate sections, including tubes of square, hexagonal, elliptical, and other unusual shapes, from thin strip (0·5 to 3·0 mm.) are described.—W. J. W.

New Control System Improves Pipe Quality. D. A. Evans. (Iron Age, 1950, vol. 165, Apr. 13, pp. 82–85). A multiple correlation test, based on values of elongation, thickness, and the carbon and manganese values, determined during the manufacture of rolled pipe, has been worked out.—J. P. S.

Tube-Reducing Mills. J. S. Blair. (Iron and Coal Trades Review, 1950, vol. 160, Jan. 13, pp. 63–71 ; Jan. 27, pp. 191–197 ; Feb. 10, pp. 305–313 ; Feb. 24, pp. 423–432, 434). This series of articles discusses in detail fundamental principles of reducing mills, including the relationships between roll speed, thickening of tube, and amount of pull. Data derived from experience and experimental work with the design and operation of this type of mill are examined. In the first part the terms for various parts and operations are defined, and changes in dimensions of the material as it passes through the rolls are considered in relation to 'no-pull,' 'pull,' and 'push' conditions. After a survey of past and present design methods, the drafting of passes is examined in detail. Part II deals with the effective radius of the rolls, and the relationship between crushing and thickening, and formulæ are derived for determining the thickness of a tube after a given reduction under various conditions. The types of roll, the shafts, and pass shapes are discussed. In Part III a theoretical no-pull and a maximum-pull mill are considered. Attention is also drawn to the types of drive which may be used and their relative advantages are outlined. In the last part practical mills, their power requirements, and motors used are described. Rules are given for calculating the thickness of tubes produced over a range of speeds. Descriptions are given of the Stüting mill, the continuous-weld mill, sizing, and other types of mills. In considering the speed control of rolls where an individual motor drive is in use, reference is made to tachometers driven by each motor, stroboscopic control as used on the Stüting mill, and the Harland electrical speed control. Finally, some details of typical mills are given.—J. C. R.

MACHINERY FOR IRON AND STEEL PLANT

Cranes in Iron and Steelworks. A. Kövesi. (Bányászati és Kohászati Lapok, 1949, vol. 4, Dec., pp. 524–539). [In Hungarian]. The various types of crane used in steelworks and their economics are discussed. The stresses in the members of the crane structure, the stability, and the power required are calculated, taking into account dynamic effects and the influence of local high temperatures. According to the author's calculations, the loads on crane bridges can be increased by 20 to 30% by modifications in the supports. The special cranes used in steelworks, *e.g.*, the open-hearth furnace charging machine, the stripper, and soaking-pit and ingot cranes are described.—E. G.

Preventing Minor Mill Delays. D. J. Kinzer. (Iron Age, 1950, vol. 165, Feb. 9, pp. 84–85). Steel mill delays are often due to the failure of limit switches on crane and transfer-car motors. Better maintenance and improved design will obviate this. Similar considerations apply in delays caused by failure of magnetic brakes.—J. P. S.

A New Type Soaking Pit Ingot Buggy. S. H. Mumma. (Iron and Steel Engineer, 1949, vol. 26, Nov., pp. 89–96). A detailed and illustrated description is given of an ingot car which delivers ingots 28 in. × 32 in. × 7 ft., weighing 15,000 lb., from soaking pits to the blooming mill at a speed of 600 ft./min. It is cable operated and is controlled by remote push buttons in the soaking-pit crane cab. The ingots are delivered automatically top or bottom first, as predetermined, on the mill approach table. The car is equipped with a hopper for collecting scale from the ingot, which is automatically dumped when the ingot is dumped. Accounts are included of the electrical equipment for driving the cable drum, and of the method of operation of the buggy. J. C. R.

PROPERTIES AND TESTS

Investigation of Failures. A. C. Ereaut. (Australian Institute of Metals : Australasian Engineer, 1949, Dec. 7, pp. 65–70). The author reports investigations of the causes of failure of parts of internal combustion engines. The failures described include : (1) Cracks in the heads of four exhaust valves of 14/14/2·5 nickel–chromium–tungsten steel about half way between stem and seat. These had their origin in machining marks on the underside of the head ; the cracks were transcrystalline and filled with oxide. (2) A diesel engine connecting rod failed because of an excessive number of large elongated non-metallic inclusions, and forging laps containing oxide. (3) Scoring of a piston and cylinder liner due primarily to the liner material being too soft.—R. A. R.

Fatigue-Testing of Valve Springs with Surface Defects. V. B. Raitses. (Zavodskaya Laboratoriya, 1949, vol. 15, Dec., pp. 1494–1496). [In Russian]. Experiments, carried out at room temperature, are described in which diesel-engine valve springs with defective surfaces were subjected to fatigue-tests at 1500 cycles/min. Metallographic examination of the springs after failure showed that fine cracks produced in the metallurgical preparation of the springs were more likely to cause early failure than those produced mechanically, *e.g.*, notches. From the experience gained, it is concluded that 15–17 million cycles give the most reliable results in the fatigue-testing of springs.—S. K.

Apparatus for the Recording, over Long Periods, of Variable Processes Having Low Frequencies and Large Amplitudes. P. G. Korolev. (Zavodskaya Laboratoriya, 1949, vol. 15, Dec., pp. 1443–1452). [In Russian]. The requirements of indicating and recording devices for the study of vibration processes of various frequencies under industrial conditions are set out, the main available types of such devices being described and the ranges of frequencies, up to 10^7 hertz, for which each type is most suited being indicated. Detailed consideration is given to indicators based on the unbalancing of a resistance-bridge or on changes in impedance, and to the continuous recording of readings by means of electromagnetic or cathode oscillographs in conjunction with 50-cycle mains current.—S. K.

Jominy Hardenability Test. J. Chodorowski. (Przeglad Techniczny, 1948, vol. 69, Sept. 15, pp. 335–340). [In Polish]. The Russian and German literature on the Jominy hardenability test is reviewed.—W. J. W.

The Shaping and Inspection of Diamond Pyramids for Use in Microhardness Testing Apparatus. E. S. Berkovich and I. V. Myakotnykh. (Zavodskaya Laboratoriya, 1949, vol. 15, Dec., pp. 1496–1499). [In Russian]. Details are given of methods found satisfactory for making diamond pyramids of exact shapes and dimensions for microhardness tests. The shaping was carried out on a disc of soft, porous, grey iron, 250–300 mm. in dia., rotating with a velocity of 1500–1800 m./min. at the circumference. The disc had been previously treated with oil-wetted diamond dust of 30–40 μ particle size, the porous nature of the surface ensuring retention of the abrasive material. The surface of the diamond in contact with the abrasive surface formed the third support of the arm holding the diamond, the other two supports being pivots of adjustable length resting on the stationary part of the machine. For the inspection of the pyramid in the course of its production, four special optical devices were used.—S. K.

Hardness and Its Measurement. W. Späth. (Metalloberfläche, 1949, vol. 3, Dec., pp. A215–A217). The disadvantages of the Brinell and Rockwell hardness scales are pointed out and the impossibility of deriving a formula to relate them is explained. The advantages of using the reciprocal of the Brinell hardness value is shown.—R. A. R.

Influence of Very Low Temperatures on the Hardness of Carbon Steels. J. Mazur. (Nature, 1950, vol. 165, Apr. 15, pp. 610–611). The effect on the hardness of carbon steels, of 0·1% to 1·25% of carbon, of immersing in liquid helium at 1·5–2·5° K. has been determined, after the specimens had already been quenched in brine. A marked increase in hardness was noted. [In the graph recording this, the numerals 1, for the untreated steel, and 3, for the helium-treated, have apparently been transposed]. The effect of tempering in boiling water and in a salt bath at 430° C. has

also been examined ; loss of hardness results, but the effect of helium cooling is still noticeable after heat-treatment.—J. P. S.

The Orientation of the Spontaneous Magnetization of Ferromagnetic Bodies. P. Henry. (Comptes Rendus, 1950, vol. 230, Jan. 2, pp. 55–56). The author presents a theoretical discussion of the influence of a magnetic field in disturbing the symmetry of the transmission of heat and of the elastic deformation of a magnetic substance. He considers that the effects suggested (which he says must certainly exist, though they have not yet been observed experimentally) explain satisfactorily why small objects of iron cannot be produced entirely free from a little remanent magnetism distributed according to their shape ; the pieces in cooling passed through the Curie point in a condition of high mechanical stress and under the influence of the earth's field.—A. E. C.

Photophoresis and Magnetophotophoresis of Particles of Omega Iron in Air at Different Pressures. P. Tauzin. (Comptes Rendus, 1950, vol. 230, Jan. 2, pp. 77–79). The attraction of some particles of iron falling in a vacuum and the repulsion of others previously referred to by the author (*see* Journ. I. and S.I., 1949, vol. 163, Dec., p. 475) has been the subject of further study. The effect was observed to become greater the higher the vacuum.—R. A. R.

Distinction between the Apparent Elastic Limit and the Limit of Magnetic Reversibility of Steel under Tensile Stress. A. Langevin, E. Paul, and M. Reimbert. (Comptes Rendus, 1950, vol. 23, Feb. 20, pp. 715–717). The inverse phenomenon to magnetostriction is a variation of the permeability under the influence of a mechanical stress. On a steel subjected to increasing static tensile stress simultaneous mechanical and magnetic measurements revealed an intermediate domain characterized by residual elongations of the order of 10^{-6} to 10^{-4} in relative value. This domain lies between the limit of magnetic and mechanical reversibilities and the apparent elastic limit. A diagram of the testing mechanism is given.

A. E. C.

Relation Between the Thermal Expansion, the Curie Temperature and the Lattice Spacing of Homogeneous Ternary Nickel–Iron Alloys. J. J. Went. (Physica, 1949, vol. 15, Sept., pp. 703–710). The importance of more experimental data concerning the exchange energy in ferromagnetic alloys is pointed out. The Curie temperature, the expansion anomaly below the Curie temperature, and the lattice spacing of 15 homogeneous, ternary, closely related, nickel–iron alloys (nickel about 46%, iron about 51%) were therefore investigated. There was a close relationship between the change in Curie temperature and the change in the expansion anomaly for the different alloys. The extent of the change in the Curie temperature depends upon the position of the third alloying element in the periodic system in relation to the position of nickel. There is no direct relation between the change in the Curie temperature and the lattice spacing.

Chrome Magnet Steels. L. H. Seabright. (Iron Age, 1950, vol. 165, Mar. 16, pp. 90–92). Steel of 3·5% chromium content for permanent magnets is made in the arc or induction furnace and rolled to the required dimensions before cooling. Starting temperatures are 1800–2100° F. (1020–1150° C.) finishing temperatures 1300–1700° F. (705–925° C.). If any machining is required annealing becomes necessary ; the most suitable treatment appears to be heating at 1525° F. (829° C.) as long as necessary to heat through, followed by a cooling cycle rapid enough to obtain the hardness required. After machining, a heat-treatment of heating to 1560° F. (855° C.) followed by oil quenching, develops magnetic properties 95% as good as those of as-rolled material.—J. P. S.

Ultrasonics—A New Chemical Engineering Tool. D. Thompson. (Chemical Engineering Progress, 1950, vol. 46, Jan., pp. 3–6). The author discusses selected applications of ultrasonic energy to the fields of chemical engineering. Four general methods of applying this form of energy are suggested : (1) As an analytical tool, *e.g.*, to study the mass of ions in an electrolyte, and to determine the size of particles in a suspension ; (2) as an engineering tool, *e.g.*, to measure thickness ; (3) to accelerate such operations as the dispersion of solids, emulsification, distillation, crystallization, and accumulation ; and (4) to promote oxidation, polymerization, depolymerization, electrolysis, and change of reaction rate.

R. A. R.

Detection of Laminations in Plates by an Ultrasonic Method. L. Kozlowski and M. Kurek. (Prace Badaweze Glownego Instytutu Metalurgii i Odlewnictwa, 1949, No. 2, pp. 99–103). [In Polish]. A series of laboratory experiments has been carried out with the 'Supersonic Flaw Detector' for the detection of internal defects in plates.—W. J. W.

Thermo-Elastic Analysis of the Allotropic Transformations of Steels. G. Vidal and P. Lescop. (Comptes Rendus, 1950, vol. 230, Jan. 9, pp. 206–208). By means of Florisson's apparatus, which measures the rate of propagation of sound in metals at any selected temperature, the authors analysed the allotropic transformations in steels by observing the variation of Young's modulus. The steels used were a heat-treated 0·9% carbon steel, two containing 0·65% and 0·9% of carbon, and one containing 0·38% of carbon, 3·7% of nickel, and 1·5% of chromium that was also examined in the heat-treated condition. The anomalies observed in curves obtained during heating and cooling are illustrated.

A. E. C.

The Mechanical Properties of Boiler Steels at Elevated Temperatures. G. Lilljekvist. (Jernkontorets Annaler, 1949, vol. 133, No. 11, pp. 519–540). An investigation of the mechanical properties, particularly the yield point, has been made of 14 Swedish boiler steels at temperatures ranging from − 40° to + 400° C. At temperatures up to about 200° C. there was relatively little scatter in the lower yield point and 0·2% proof stress results, but in the 250–300° C. range some lower yield point readings deviated from the mean values by ± 2 to 3 kg./sq. mm. The fall in lower yield point and 0·2% proof stress with rising temperature was practically the same for killed and rimming steels, and the initial dimensions and heat-treatment of the material also did not appreciably affect the shape of the yield-point/temperature curves.—R. A. R.

The Behaviour of a Nominally Isotropic 0·17 per cent Carbon Cast Steel under Complex Stress Systems at Elevated Temperatures. A. E. Johnson. (Proceedings of the Institution of Mechanical Engineers, 1949, vol. 161, W.E.P. No. 51, pp. 182–186). To obtain relations between stress, strain, time, and temperature, to afford a basis of design in cases where steels are subjected to plastic deformation under general stress systems at elevated temperatures, pure tensile and torsion tests have been made at temperatures of 20°, 150°, 350°, 450°, and 550° C. at various rates of stressing on an isotropic 0·17% carbon cast steel. The results have been analysed. It seems probable that this steel behaved anisotropically under the relatively high plastic strains of the short-time tensile and torsion tests. Such anisotropy appears to be a function of the strain applied, and not entirely due to the initial condition of the material. It seems possible that it is of a reasonably simple nature, but complex stress tests are necessary to illustrate its details.—R. A. R.

Heat-Resisting Materials for Design Purposes. R. Skorski. (Przeglad Techniczny, 1948, vol. 69, Feb. 1, pp. 38–42). [In Polish]. The author gives a brief review of existing heat-resisting materials (mostly for turbine blades) in England, Germany, and the U.S.A. New ways of testing appropriate materials based on titanium and boron by determining the hardness of the carbides are given.—W. J. W.

Heat-Resisting Metallic Materials. A. Bargone. (Máquinas e Metais, 1949, Oct., p. 3 ; Nov., pp. 5–6). [In Portuguese]. The author enumerates the classes of steel used for temperatures ranging up to 900° C. and briefly discusses materials for electric resistances.—R. S.

Some Characteristics of the Principal Alloys for Gas Turbines. J. B. de Nardo. (Ingenieria e Industria, 1949, Oct., pp. 80–83). [In Spanish]. The basic requirements of materials for the construction of gas turbines are : High mechanical resistance at high temperature ; good resistance to primary and secondary creep ; and resistance to oxidation, corrosion, and erosion. The phenomenon of creep is briefly described. Attention is drawn to the differing requirements for aeronautic and land gas turbines. An account of the heat-treatment of these alloys is given.—R. S.

Analysis of Interstitial Diffusion Using Activity Methods. A. G. Guy. (Transactions of the American Institute of Mining and Metallurgical Engineers, 1949, vol. 185, pp. 607–610 ; Journal of Metals, 1949, vol. 1, Sept.). The work described had the purpose not only of providing a superior analysis of interstitial diffusion, but also of indicating a possible approach to the more important question of an adequate treatment of substitutional diffusion. An equation

that permits the direct treatment of activities was developed. A convenient approximate solution of this equation was used to analyse the data of C. Wells and R. F. Mehl (Transactions of the American Institute of Mining and Metallurgical Engineers, 1940, vol. 140, p. 279) for the diffusion of carbon in iron to determine diffusion constant values. The results agreed well with those obtained by these two investigators.
R. E.

Boron in Steel. (Iron and Coal Trades Review, 1950, vol. 160, Jan. 20, pp. 150–152). This is an English summary of a paper by Potaszkin read before the Société Française de Métallurgie dealing with the influence of small additions of boron on properties of medium-carbon steels. The experimental work is described and the following conclusions are reached : (1) A content of at least 0·008% boron, added as ferroboron, increases the tendency to austenite grain growth and increases hardenability, tensile strength, elastic limit, reduction of area, and the quality coefficient of impact. As the base steel had low hardenability, drastic (water) cooling of thin sections was necessary before this action of boron was realized. (2) The improvement in mechanical treatment was greatly increased after tempering at 650° C. (3) Where the speed of cooling was slower (air or oil) boron caused grain growth thereby lowering the mechanical properties, particularly elastic limit and impact strength, as compared with those of the base steel. (4) In the annealed condition tensile strength was also reduced.—J. C. R.

Pure Iron and the Properties of Its Surface. H. Kalpers. (Metalloberfläche, 1949, vol. 3, Dec., pp. A218–A219). The properties and applications of very pure iron (99·85% and higher) are reviewed. Its electrical conductivity is 25% higher than that of mild steel. Its resistance to rusting and chemical attack is very high. It oxidizes at elevated temperatures, but at up to about 600° C. the scale adheres so firmly that it offers a high resistance to further oxidation. It has excellent drawing properties and offers a good surface for coatings of zinc, paint, or enamel.—R. A. R.

The Development of Cast Iron during the Last 25 Years. M. Ballay and R. Chavy. (International Foundry Congress 1949 : Metalen, 1950 Congress Number, Part I, pp. 55–64). In reviewing the cast irons with improved properties which have been developed during the last 25 years, the authors cover the subject in the following sections : (1) Unalloyed grey iron ; (2) alloyed grey iron ; (3) the improvement and the hardness of grey iron by heat-treatment ; (4) white cast iron ; and (5) heat-resisting and corrosion-resisting irons.—R. A. R.

Progress in High Duty and Alloy Cast Iron. A. B. Everest. (Metallurgia, 1949, vol. 41, Dec., pp. 84–88). Most of this review of developments in special cast irons is devoted to cast iron with spheroidal graphite, its manufacture, heat-treatment, and applications being briefly dealt with. Some applications of Ni-Hard, Ni-Resist, and Minovar—the last being a low-expansion cast iron for castings in high-precision machine tools—are also mentioned.—R. A. R.

The Relation between the Saturation Factor and the Strength of Cast Iron. F. Roll. (Neue Giesserei, 1949, vol. 36, Dec., pp. 378–380). Specimens of a large number of cast irons from eight different foundries have been tested to see whether there was a relationship between the Tobias and Brinckmann carbon saturation factor S_c and the tensile strength ($S_c = C/(4{\cdot}23 - 0{\cdot}312Si + 0{\cdot}33P + 0{\cdot}66Mn)$). No relationship was found, and it remains to be seen whether the microstructure, particularly the nature of the graphite, must also be brought into the picture.—R. A. R.

Quality Control of Production. C. Sapegno. (Metallurgia Italiana, 1949, vol. 41, Sept.–Oct., pp. 271–278). The author describes a method of controlling the quality of alloy steel, in which mechanical and microscopical tests are carried out on specimens cut from the billets rolled from a 150-kg. ingot.

Sintered Hard Metals Containing Titanium Carbide. E. J. Sandford. (Alloy Metals Review, 1949, vol. 7, Dec., pp. 2–11). The theories advanced to explain the beneficial effect of titanium carbide when machining steel are outlined and manufacturing difficulties which arise when this carbide is used, and its effects on the physical properties and structure of the hard metal are discussed. Attempts to displace tungsten carbide wholly by other carbides, especially titanium carbide, have entirely failed in alloys used for metal cutting.
R. A. R.

Certain Characteristics of the Flat-Bottom Rail, with Special Reference to the Shape. C. M. Krüger. (Journal of the South African Institution of Engineers, 1949, vol. 48, Nov., pp. 85–104). The evolution of the flat-bottom rail section from 1831 to modern times is sketched. The most economic section and an ideal shape of rail are discussed and factors affecting wear resistance, *i.e.*, the chemical composition, heat-treatment, and grain-size are also dealt with.—R. A. R.

Developments in Alloy Steels. T. H. Arnold and C. V. Mills. (Metallurgia, 1949, vol. 41, Dec., pp. 75–78). Developments in some special steels for high-temperature applications, corrosion and wear resistance, high-strength welding electrodes (called ' Fortiweld '), and for cold rolling aluminium alloy strip (' Hadura ' steel) are reviewed.—R. A. R.

New Precipitation-Hardening Stainless Steels. G. N. Goller and W. C. Clarke, jun. (Iron Age, 1950, vol. 165, Mar. 2, pp. 86–89 ; Mar. 9, pp. 79–83). Two new steels 17-4PH and 17-7PH have been developed by the Armco Steel Corp., Baltimore. The first of these, 17-4PH, developed primarily for bar and forging billet applications, contains C 0·05% Cr 16·5%, Ni 4·0%, and Cu 4·0%. It is austenitic at the annealing temperature of 1800–1850° F. (980–1010° C.) but transforms to a mixture of austenite and martensite on cooling below 250° F. (120° C.) ; the precipitation-hardening treatment consists of a 1-hr. treatment at 900° F. (480° C.) when a highly dispersed copper-rich phase precipitates. The ultimate strength in this condition is about 89 tons/sq. in., the elongation 6–15%, and the Brinell hardness 375–440. The endurance limit for 10^8 stress reversals is between 33·5 and 35·7 tons/sq. in. Corrosion resistance is equal to that of type 304 (C 0·08%, Cr 18–20%, Ni 8–11%, Mn 2·0% max.) stainless steels. Welding qualities are excellent, and if a filler rod of the same material is used, the weld can be heat-treated to a joint efficiency of 98%. The second steel, 17-7PH, intended for sheet, strip, plate, and wire applications employs aluminium as the precipitation-hardening element, a typical composition being C 0·07%, Cr 17·0%, Ni 7·0%, Al 1·0%. On quenching from 1800–1950° F. (980–1065° C.) a soft temper is produced, the heat-treatment necessary for hardening being : (1) A treatment at 1400° F. (760° C.) for 30 min. to 3 hr. followed by quenching or air-cooling ; (2) a treatment at 900–950° F. (480–510° C.) for 30 min. to 1 hr. followed by air cooling. In this condition, its ultimate strength is 82·5–91·5 tons/sq. in., its elongation 7–12%, and Rockwell ' C ' Hardness 40–50. In extra hard temper, wire of tensile strength from 116 to 154 tons/sq. in. may be produced. The fatigue properties are similar to those of 17-4PH. Arc-welded joints of good strength can be made but, owing to the loss of aluminium during welding, it is advisable to use 17-4PH filler rods.—J. P. S.

METALLOGRAPHY

The Mitsche-Reichert Eyepiece for Measuring Grain-Size and Structure. R. Mitsche. (Berg- und Hüttenmännische Monatshafte der Montanistischen Hochschule in Leoben, 1949, vol. 94, Dec., pp. 361–362). An eyepiece for a metallurgical microscope is described. Its object is to enable the grain-size, quantity, and distribution of slag inclusions, graphite, etc., to be rapidly determined by an observer who need not be a trained microscopist. The eyepiece carries a glass disc with a series of seven hexagonal graticules of different dimensions ; the disc can be turned so as to bring the graticule of the desired size to cover the image. The magnification of the two objectives and the dimensions of the graticules are selected so that the A.S.T.M. grain-sizes 1 to 10 can be determined with a disc with only seven graticules.
R. A. R.

A Simply Constructed Camera for Use in Photomicrography. D. Y. Dollman. (Chemist Analyst, 1949, vol. 38, Dec., pp. 80–81). Instructions are given for making a simple box camera $6 \times 7\frac{1}{2} \times 4\frac{1}{2}$ in. to fit over the eyepiece mount of a microscope.—R. A. R.

Study of Metallic Surfaces with the Electron Microscope. W. Feitknecht and K. Huber. (Metallurgia Italiana, 1950, vol. 42, Feb., pp. 53–57). The different methods used to obtain the replica of the etched metal for examination under the electronic microscope are described. Etching was always preceded by electrolytic polishing. The paper is illustrated by a number of photomicrographs of various metals, showing corrosion figures, obtained with the electron microscope of

the Institute of Inorganic Chemistry and Physics of the University of Berne, Switzerland.—R. F. F.

The Electron Microscope and Its Application to Metallurgy. A. Saulnier. (Revue de l'Aluminium, 1949, vol. 26, Nov., pp. 355–360). An account is given of the principle underlying the operation of the electron microscope which has a magnification of over 50,000. A note is included on the preparation of specimens and micrographs are shown of some non-ferrous alloys.—J. C. R.

The Mechanism of Martensite Formation. A. B. Greninger and A. R. Troiano. (Transactions of the American Institute of Mining and Metallurgical Engineers, 1949, vol. 185, pp. 590–598 : Journal of Metals, 1949, vol. 1, Sept.). An X-ray and microscopical investigation of the martensite transformation in steels containing about 22% of nickel and 0·8% of carbon was carried out to study : (1) The accurate evaluation of the lattice relationship between austenite and individual crystals of martensite ; and (2) the measurement and analysis of the change in position that a volume of austenite undergoes when it transforms into a crystal of martensite. For this latter study, the stereographic analysis of martensite shear was used, and a description of the method is appended to the paper.—R. E.

Equilibrium Interferences in the γ–α Transformation of Iron because of Lack of Diffusion. A. Wüstefeld. (Archiv für Metallkunde, 1949, vol. 3, Dec., pp. 436–438). The author shows by experiments and calculations that a non-ageing steel can lose its stability by an annealing treatment at above A_1. Conversely, it should be possible to render stable a steel which is naturally ageing-sensitive by cold deformation followed by a long anneal at below the transformation temperature. Other investigators have found that this can be done.—R. A. R.

CORROSION

The Corrosion of Metals. W. H. J. Vernon. (Cantor Lecture : Journal of the Birmingham Metallurgical Society, 1949, vol. 29, Dec., pp. 198–221). *See* Journ. I. and S.I., 1950, vol. 164, Feb., p. 247).

The Underground Corrosion of Ferrous Metals in the Light of Recent Research. K. R. Butlin and W. H. J. Vernon. (Society of Chemical Industry, Chemical Engineering Group. Dec., 1949, Advance Copy). After considering the theories for the corrosion of buried ferrous metals the theory of von Wolzogen Kühr, who showed that the sulphide on the exterior of corroded pipes in wet clay soils was produced by the organism *Desulphovibrio desulphuricans*, is discussed. This theory has been supported by substantial evidence and the work of other investigators. A brief account of the fundamental studies on sulphate-reducing bacteria at the Chemical Research Laboratory is then given. Several promising inhibitors of the growth of these sulphate reducers have been found, *e.g.*, potassium tellurite, cetyl pyridinium bromide, *o*-nitrophenol, and potassium dichromide. Finally a report on field investigations of the corrosion of buried pipelines is made in which there is much evidence of corrosion and leakages in soils and clays carrying sulphate-reducing bacteria, and a striking example of cast-iron and steel pipes in wet heavy clay subsoil having an abnormally low sulphate content where there was virtually no corrosion.—R. A. R.

Correlation between Corrosion Survey Results and Actual Conditions as Determined through 130 Miles of Continuous Reconditioning. I. B. Tietze. (Corrosion, 1949, vol. 5. Dec., pp. 409–415). Surveys have been made of buried 8-in, dia. steel pipelines by (*a*) walking the line and locating by visual means alone portions likely to be corroded, and (*b*) measuring pipe-to-soil potentials at places where corrosion was expected. Continuous reconditioning was subsequently carried out on some sections of the line, and 'spot' reconditioning at others. The data obtained are correlated in an attempt to assess the value of the surveys. It is found that spot reconditioning in accordance with survey recommendations is not effective for long periods without supplementary cathodic protection.—R. A. R.

Corrosion Problems in the Pulp and Paper Industry. R. P. Whitney. (Corrosion, 1949, vol. 5, Dec., pp. 435–439). The more important corrosion problems encountered in the pulp and paper industry are discussed under the headings sulphite pulping, alkaline pulping, bleaching, and papermaking. It is found, in general, that materials reasonably resistant to corrosion are available, but the high cost of the stabilized stainless steels is a matter of complaint.—R. A. R.

Plant Corrosion in the Fatty Acid Industry. R. J. Paul. (Corrosion, 1949, vol. 5, Dec., pp. 439–442). The paper gives a brief outline of materials used for equipment, pumps, and piping in the older processing methods, followed by a summary of new material applications in recent processes. Specific corrosion rates in inches per year are not given, but the relative suitability of stainless steels and non-ferrous metals for various plant items in the treatment of fatty acids are discussed.—R. A. R.

Evaluation of the Effects of Rust on Steel Sheets. V. Montoro and G. Canesi. (Metallurgia Italiana, 1949, vol. 41, Sept.-Oct., pp. 225–228). The authors have studied a method of impact test which will show, on a metal which has been subjected to corrosion, the effects of corrosion, both localized and in depth. Tests of this type, and tensile tests, have been carried out on rusted steel sheets of normal composition. The decrease in mechanical efficiency can be converted into an equivalent decrease of thickness by making use, in the case of the tensile test, of the relation of inverse proportionality between the ideal and apparent values of the thickness and breaking load, and, in the case of the impact test, of the linear relation between the thickness of the test piece and the logarithm of the energy absorbed by the impact.—R. F. F.

Corrosion Fatigue—The Influence of Disarrayed Metal. D. Whitwham and U. R. Evans. (Journal of The Iron and Steel Institute, 1950, vol. 165, May, pp. 72–79). It is not certain from theory whether a preliminary period of dry fatigue should lengthen the normal corrosion-fatigue life by strain-hardening, or shorten it by producing disarrayed metal which may be particularly susceptible to corrosion. An answer to this question was obtained by carrying out two-stage tests ; a period of dry fatigue was followed by corrosion fatigue up to failure ; for comparison, a second set was submitted to corrosion fatigue without previous dry fatigue. With both cold-drawn and annealed wires, little or no change in corrosion-fatigue life was brought about by preliminary dry fatigue under the conditions tested. A metallographic study was also made of changes during air-fatigue and corrosion-fatigue processes. For this purpose, the annealed wires were reduced by electropolishing to remove surface defects and to avoid deformation. In air fatigue, the repeated application of a stress, greater than the fatigue limit, results in the plastic deformation of many grains as a preliminary to the development of micro-cracks and failure. Simultaneously, heat is generated in the specimen and a superficial oxidation of the surface follows. In corrosion fatigue, at a stress below the air-fatigue limit, a localized attack leads to stress intensification and hence to corrosion along slip bands. Attack spreads around the circumference of the wire, with subsequent weakening. The major damage, estimated by loss in tensile strength, occurs towards the end of the process, both in air fatigue and corrosion fatigue. Cracking is mainly transcrystalline, but may occasionally be intercrystalline for distances of a few grain diameters.

Optical Studies of the Oxidation of Iron at Temperatures in the Range 20–265° C. A. B. Winterbottom. (Andrew Carnegie Research Report : Journal of The Iron and Steel Institute, 1950, vol. 165, May, pp. 9–22). Optical investigations into the surface oxidation of iron and some ferrous alloys at temperatures in the range 20–265° C. were carried out, using an improved experimental technique. Methods have been evolved for applying the strict classical theory of film optics to the evaluation of the results. The apparatus is briefly described. Results show that films up to 100–250 Å. in thickness consist mainly of magnetite, or possibly γ ferric oxide, while on films of greater thickness an outer layer of α ferric oxide is formed.

The law of growth of films is probably parabolic after the initial transient phenomena, and the rate appears to depend on crystal orientation, atmospheric moisture, and polish and cold work. The last retards film growth, possibly as a result of preferred orientation. The constitution of the film appears to be independent of atmospheric moisture. The growth process seems to be of the same character from room temperature up to 400–500° C., and does not appear to depend upon whether the film is formed on iron, or on ferrous alloys of the stainless type, containing nickel or chromium.

Contribution to the Study of the Surface Oxidation of Metals at High Temperatures. J. Bénard. (Metallurgia Italiana,

1950, vol. 42, Jan., pp. 3–6). [In French]. Oxidation tests carried out at high temperatures on iron and copper clearly showed the influence of the crystal structure. Metals work-hardened by rolling or drawing, and annealed to remove this effect, but not the preferential orientation, showed definite variations in the speed of oxidation. Similar variations are caused by work-hardening due to mechanical polishing. The lattice orientation of the oxide layers might be determined from that of the metal at the surface.—R. F. F.

ANALYSIS

Rapid Photometric Processes in the Foundry Laboratory. H. Pinsl. (Neue Giesserei, 1949, vol. 36, Dec., pp. 380–386). Rapid procedures are described for the photometric determination of phosphorus, manganese, silicon, copper, vanadium, titanium, nickel, cobalt, chromium, and molybdenum in cast iron.—R. A. R.

Chromium and Manganese in Steel and Ferroalloys. J. J. Lingane and J. W. Collat. (Analytical Chemistry, 1950, vol. 22, Jan., pp. 166–169). The simultaneous spectrophotometric determination of chromium and manganese is described. This is based on the measurement of the cumulative absorbtion by the dichromate and permanganate ions at 440 and 545 mμ. Provided the spectrophotometer has a narrow band width, $\leqslant 5$ mμ, and that the solutions contain at least 0·5 *M* sulphuric acid, the absorbtion complies with Beer's law. At these wavelengths, ferric iron and the ions of nickel, cobalt, and vanadium have appreciable absorbtion and corrections have been established : the correct state of oxidation of the chromium and manganese is brought about by the use of potassium disulphate and potassium periodate.—J. P. S.

Volumetric Determination of Titanium in Ferrotitanium. F. Delicado Martinez. (Instituto del Hierro y del Acero, 1949, vol. 2, Oct.–Dec., pp. 67–69). [In Spanish]. A volumetric method for the determination of titanium is described, which avoids the interference of aluminium without necessitating previous separation. Trivalent titanium is oxidized to tetravalent titanium with $KMnO_4$, and an external indicator is used for the better determination of the end-point.—R. S.

The Isolation of Carbides from High-Speed Steel. D. J. Blickwede and M. Cohen. (Transactions of the American Institute of Mining and Metallurgical Engineers, 1949, vol. 185, pp. 578–584 : Journal of Metals, 1949, vol. 1, Sept.). The authors describe experiments using the citrate cell and hydrochloric acid cell methods for isolating the carbides from both annealed and hardened M-2 tungsten–molybdenum high-speed steel. Particular attention was paid to the amount, as well as the composition, of the carbides so that the matrix analysis became ascertainable by subtraction from the overall steel composition.—R. E.

Identification of Pobedites with the Help of a Steeloscope. A. A. Dobrinskaya and E. P. Selyanynova. (Zavodskaya Laboratoriya, 1949, vol. 15, Dec., pp. 1480–1482). [In Russian]. The spectroscopic identification of various types of the pobedite (sintered carbide) pressed powder products is described. For the production of the spectrum a 5-amp. A.C. arc with a fixed copper electrode was used, observations being made with an auto-collimating steeloscope. As standards for the determination of titanium and cobalt, the lines of tungsten were used, while the lines Ni 5080·62 Å and Mo 5533·05 Å were employed for nickel and molybdenum, respectively. It was found most convenient to start the analysis with the determination of nickel, and experiments showed that it is necessary to allow 30–40 sec. after the striking of the arc for the intensity of the nickel line to become steady.—S. K.

Vacuum Fusion Furnace for Analyses of Gases in Metals. W. G. Guldner and A. L. Beach. (Analytical Chemistry, 1950, vol. 22, Feb., pp. 366–367). A new all-glass vacuum furnace for the determination of gases in metals is described, in which the crucible consists of a graphite tube packed inside a quartz tube with graphite powder. This quartz tube is suspended, clear of the sides, in the vacuum tube of the apparatus and heated by an external induction coil of copper tubing.—J. P. S.

BOOK NOTICES

AMERICAN WELDING SOCIETY. "*Welding Handbook.*" Third Edition. 8vo, pp. xii + 1651. Illustrated. New York, 1950 : American Welding Society. (Price $13.00)

During the last World War, one of the most widely used reference books in America and this country on all branches of welding was the 1942 edition of the American Welding Society's Handbook. The long-awaited third edition has now appeared and there is little doubt that excellent though its predecessor was, it is surpassed by far in completeness and accuracy by the present edition.

The aim of the book is to cover all aspects of welding. This formidable task has been tackled in an extremely exhaustive manner, and where space limitations have precluded reference to some subjects only remotely connected with welding, this deficiency, if such it can be called, has been rectified by bibliographies appearing at the end of each chapter. These bibliographies list the more important books, articles, codes, and specifications bearing on the subjects dealt with in the chapter in question.

Obviously, one author could never have contemplated the preparation of a book such as this, by reason of the extremely wide range of knowledge required. In actual fact, 250 separate authors have been involved, and their efforts have been co-ordinated in a most admirable fashion by a committee of eight experts whose experience covers a representative cross-section of American industry.

More than 30 welding and cutting processes at present in use are described in 27 different chapters. Thirteen chapters are devoted to the welding of various metals, and 11 chapters deal with design and inspection requirements. Additional chapters give data on estimating, physics of welding, welding terms and definitions, weld tests, and filler metal specifications.

Of particular interest are the chapters on the newer processes. Pressure gas welding and inert gas welding are dealt with in great detail, but induction welding, which is beginning to cause much interest, is dismissed in a couple of pages without giving any details as to how it is accomplished. The growing use of clad steels and applied liners for pressure and chemical vessels, on the other hand, is adequately covered by two very comprehensive chapters which leave little further to be said on these subjects.

It is very difficult indeed to say briefly the type of person for whom this book is particularly intended, because of its wide scope. Generally speaking, it should be possessed by all interested in any form of welding, and in particular, the welding engineer, inspector, designer, student, and all users and manufacturers of welding equipment.

In using the book in this country, some difficulty may arise from the fact that British and American specifications for arc-welding electrodes are not the same. The American method of classification is, however, quite clear after study and, for further assistance in comparing British and American electrodes, reference should be made to the B.E.A.M.A.–I.O.W. Electrode Classification in which an effort at cross-reference has been made.

At one time, there were great differences between British and American practices in matters such as the specification of screw threads, and drawing-office practice. At the Ottawa conference on the unification of engineering standards in 1945, the need for co-ordination between British and American practices was recognized, and already some British Standards have been revised with this object in view. The new proposed scheme of symbols for welding is very much in line with that in use in America, and in this respect, the Welding Handbook will be of much greater value in this country than would otherwise have been the case.

A really satisfactory index in a book of this size might be considered too much to expect, but it is a great relief

to find the 69-page index almost fool-proof. This index is really a noteworthy achievement, and accuracy and completeness here have obviously been recognized by the editors as essential in enhancing the value of the book.

A. J. HIPPERSON.

BROOKE, E. H. "*Appendix to Chronology of the Tinplate Works of Great Britain* 1665–1949." 8vo, pp. 179–241. Cardiff, 1949 : William Lewis (Printers) Ltd. (Price 5*s*.)

The Chronology was published in 1944 and contained particulars extracted from the records of the author and his father C. B. Brooke, which have been kept for an unbroken period of over 80 years, regarding the tinplate works (and certain closely associated steel and galvanizing plants) in Great Britain. In the present Appendix the changes that have taken place during the past five years have been classified and some slight errors corrected.—R. E.

CRAFTS, W., and J. L. LAMONT. "*Hardenability and Steel Selection*." 8vo, pp. xiii + 279. Illustrated. London, 1949 : Sir Isaac Pitman and Sons, Ltd. (Price 35*s*.)

This book contains information on hardenability that previously has been available only in a vast number of scattered articles in many publications available to the metallurgist only after laborious research and considerable expense. In order to facilitate the use of this accumulated information, the authors have prepared this book which consolidates and summarizes all the work that is well supported by practical evidence.

The first introductory chapter is followed by a chapter dealing with the heating of steel for hardening. The authors point out that the effective heat-treatment requires austenitization at 30° to 85° C. above the critical temperature depending upon the composition of the steel, its initial condition, and time at temperature. This temperature should also be consistent with the grain-size characteristics of the steel and the grain-size desired in the product. Chapter 3 deals with the transformation of the austenite and gives particulars of its study by continuous cooling methods and by isothermal methods. The formation of bainite and martensite is also dealt with at considerable length. Of particular interest is the section dealing with the general effects of the alloying elements on isothermal transformation of austenite. Chapter 4 on quenching is particularly comprehensive and, amongst other things, deals exhaustively with the Jominy test as applied to round bars, squares, flats, and plates. Chapter 5, which is devoted to a consideration of hardness and hardenability, is of considerable theoretical and practical interest. The authors say that the high hardness of steel is due primarily to the obstruction offered by the carbide particles to the ease with which the soft ferrite flows under stress, as has been shown by the work of Gensamer, Pearsall, Pellini, and Low, who evaluated the effect of carbides in terms of the average distance in which the ferrite was free to slip without interference between carbide particles.

Chapter 6 deals with practical aspects of methods of determining hardenability. Chapter 7 deals with Jominy hardenability control and contains sections devoted to the calculation of the Jominy curve for ideal critical diameter, giving several practical examples. Chapter 8 is concerned with tempering after hardening, and Chapter 9 with mechanical properties and hardenability. Chapter 10 on factors in the selection of steel will be of particular interest to all steel users. It considers the properties affecting serviceability, factors affecting hot working and machining, and points out that selection requires first an appraisal of the service requirements and that, in spite of the wide variety of available steels, only one or two are outstandingly economical at each strength level.

J. FERDINAND KAYSER.

DEUTSCHE GESELLSCHAFT FÜR CHEMISCHE APPARATEWESEN E.V. "*Achema Jahrbuch, 1940–1950*." 8vo, pp. 704. Illustrated. Frankfurt am Main, 1950 : Dechema.

This volume was prepared in connection with the IXth Achema Exhibition and Convention on Chemical Works Plant and Laboratory Apparatus at Frankfurt am Main, July 9–16, 1950, where it was distributed free to visitors. A general section, of 50 pages, contains articles on the development of the German chemical industry and its reconstruction since the war, as well as messages from leading German chemists. The next 185 pages contain reports on their own products contributed by 124 firms; then follows a directory, occupying 192 pages, and containing 19,000 entries of manufacturers of plant and apparatus. The book ends with 150 pages of displayed advertisements. Some 20 pages are interleaved.—J. P. S.

FÉDÉRATION DES INDUSTRIES BELGES. "*General Guide-Book of Belgian Industrial Production*." La. 8vo, pp. 372. Brussels, 1949 : Fédération des Industries Belges.

The purpose of this guide-book is to give foreign buyers information concerning the various articles manufactured in Belgium. The industries covered include iron and steel, non-ferrous metals, ceramics, mining, and chemical. The names and addresses of the manufacturers are not given, but for the different industries the names and addresses of the appropriate industrial Federations (forming the Fédération des Industries Belges) to whom inquiries should be sent, are included.—R. E.

GMELINS HANDBUCH DER ANORGANISCHEN CHEMIE. Achte Auflage. System-Nummer 68. "*Platin*." Teil A—Lieferung 5 : "*Die Legierungen der Platinmetalle : Ruthenium, Rhodium, Palladium*." La. 8vo, pp. 183. Clausthal-Zellerfeld, 1949 : Gmelin-Verlag G.m.b.H. (Price DM 43.–)

This section of the well-known Gmelins handbook covers, in a most comprehensive manner, the alloys of the platinum metals ruthenium (24 pages), rhodium (21 pages), and palladium (149 pages). Phase diagrams for several of the more important alloys are presented as well as many graphs to show their properties. The information is based on the literature up to June 30, 1948, and for patents, the reader is referred by tables, one for each of the more important alloys, to the appropriate page numbers in A. Grützner's and C. Götze's "*Patentliteratur über die Legierungen der Platinmetalle*."

In presenting this volume the publishers announce that by carefully summarizing the subject matter and keeping strictly within the sphere of interest, they hope to reduce the delays which war and post-war conditions imposed on the preparation of new Sections. In accordance with the new plan the series is expected to be completed in ten to twelve years. It has also been decided that all new Sections will be based on the literature to the end of 1949, and supplementary volumes will be issued to bring the older Handbooks up to the same date.—R. A. R.

JESSOP, H. T., and F. C. HARRIS. "*Photoelasticity. Principles and Methods*." 8vo, pp. viii + 184. Illustrated. London, 1949 : Cleaver-Hume Press, Ltd. (Price 28*s*.)

This publication is a complete textbook on the theory of photo-elasticity and of the application of photo-elasticity to stress problems.

The first seven chapters are purely theoretical and cover stresses, strain and stress-strain relations, optics, polarization and double refraction, theory of photo-elasticity, reduction, the interpretation of observations, and stresses in three dimensions.

Chapter 8 is the first practical chapter and deals comprehensively with the bench for photo-elastic work. Although not a long chapter, it is so well and clearly written that it contains all the information necessary for the construction of photo-elastic apparatus. Earlier works on photo-elasticity usually described only the use of Nicol prisms and mica quarter-wave plates. The present authors point out that although Polaroid does not polarize completely in the violet end of the spectrum, this does not materially affect its efficiency for photo-elastic observations even with white light, and, as it can be obtained in sheets of up to 12 in. in diameter, one can economically work with very large fields. The authors also give details of three possible substitutes for mica quarter-wave plates.

Chapter 9 is equally practical and comprehensive. Here the reader will find described the various materials that are used for the construction of models, together with full details for their initial annealing, the machining of the models, polishing, loading, etc. The frozen-stress procedure is also adequately described.

Chapter 10 is devoted to a consideration of examples of stressed members, *viz*., a circular disc under thrust along a diameter, a rectangular block with square holes under vertical thrust, a simply supported rectangular beam under central concentrated load, a shaped bar with a central circular hole under tension, and a railway wagon coupling hook.—J. FERDINAND KAYSER.

NEW PUBLICATIONS

ANGLO-AMERICAN COUNCIL ON PRODUCTIVITY. "*Drop Forging. Report of a Visit to the U.S.A. in* 1949 *of a Productivity Team Representing the Drop Forging Industry.*" London: Anglo-American Council on Productivity. (Price 2*s.* 3*d.*)

ANGLO-AMERICAN COUNCIL ON PRODUCTIVITY. "*Materials Handling in Industry.*" Report of an Investigation Made by a Group Appointed by the Council. London: Anglo-American Council on Productivity. (Price 2*s.* 6*d.*)

BARRET, P. "*La Mesure des Températures de Flammes.*" (Publications Scientifiques et Techniques du Ministère de l'Air. Notes Techniques No. 33). 8vo, pp. 42. Paris, 1950: Service de Documentation et d'Information Technique de l'Aéronautique. (Price 300 francs)

BRITISH IRON AND STEEL RESEARCH ASSOCIATION. "*A Summary of the Proceedings of the Conference on Foundry Steel Melting.*" 4to, pp. 73. London: The Association. (Price 10*s.*)

BRITISH STANDARDS INSTITUTION. B.S. 292: 1950. "*Dimensions of Ball Bearings and Parallel-Roller Bearings.*" 8vo, pp. 67. London: The Institution. (Price 6*s.*)

BRITISH STANDARDS INSTITUTION. B.S. 482: 1950. "*Wrought Iron and Mild Steel Hooks for Cranes, Chains, Slings, Blocks and General Engineering Purposes (Excluding Building Operations).*" 8vo, pp. 35. London: The Institution. (Price 5*s.*)

BRITISH STANDARDS INSTITUTION. B.S. 1630–32: 1950. "*Corrosion-Resisting Alloy Steel Castings.*" 8vo, pp. 14. London: The Institution. (Price 2*s.*)

BRITISH STANDARDS INSTITUTION. B.S. 1640: 1950. "*Steel Butt-Welding Fittings for the Petroleum Industry.*" 4to, pp. 17. London: The Institution. (Price 7*s.* 6*d.*)

BRITISH STANDARDS INSTITUTION. B.S. 1641: 1950. "*Cast Iron Pipe Fittings for Sprinklers and Other Fire Protection Installations.*" 8vo, pp. 19. London: The Institution. (Price 2*s.* 6*d.*)

BRITISH STANDARDS INSTITUTION. B.S. 1648: 1950. "*Heat-Resisting Alloy Steel Castings.*" 8vo, pp. 5. London: The Institution. (Price 2*s.*)

CAMBON, T. "*Contribution á l'Emploi des Méthodes Optiques en Métallographie Microscopique.*" Application aux Bronzes, aux Alliages Cuivre-Antimoine et a une Série de Siliciures. (Publications Scientifiques et Techniques du Ministère de l'Air. No. 236). 8vo, pp. 107. Illustrated. Paris, 1949: Service de Documentation et d'Information Technique de l'Aéronautique. (Price 500 francs)

COLVIN, F. H., and F. A. STANLEY. "*Grinding Practice.*" Third Edition. La. 8vo, pp. 419. New York, 1950: McGraw-Hill Book Co., Inc. (Price $3.75)

DANESE, G. "*Impianti siderurgici; impianti industriali meccanici in generale; materie prime per l'industria siderurgica: produzione della ghisa, fabbricazione dell' acciaio.*" Pp. xii + 452. Illustrated. Genoa, 1949: I. Briano. (Price 2800 lire)

ECK, B. "*Technische Strömungslehre.*" 3. Auflage. 8vo, pp. x + 398. Illustrated. Berlin, Göttingen, Heidelberg, 1949: Springer-Verlag. (Price DM 27.–)

FAHRENBACH, W. "*Widerstandsschweissen.*" (Heft 73 der Schriftenreihe "Werkstattbücher." Herausgegeben von H. Haake). 2. Auflage. Pp. 64. Illustrated. Berlin, Göttingen, Heidelberg, 1949: Springer-Verlag. (Price DM 3.60)

FLIMM, J. "*Werkstoffe.*" Band 1. "*Legierungsbildung—Stahl und Eisen.*" Pp. 174. Illustrated. Kiel, 1950: Georg Westermann Verlag. (Price DM 9.40)

GÖNNER, O. "*Die elektrische Widerstandsschweissung und ihre praktische Anwendung.*" 3., erweiterte Auflage. 8vo. pp. 189. Illustrated. Munich, 1949: Carl Hanser-Verlag. (Price DM 7.50)

GRANT, Sir ALLAN. "*Steel and Ships.*" London: Michael Joseph, Ltd. (Price 15*s.*)

GURNEY, R. W. "*Introduction to Statistical Mechanics.*" 8vo, pp. vii + 268. Illustrated. New York and London: McGraw-Hill Book Co., Inc. (Price $5.00, 42*s.* 6*d.*)

HAYES, H. "*Drop Forging.*" Second Edition. Sm. 8vo, pp. ix + 105. Illustrated. London, 1950: Sir Isaac Pitman and Sons, Ltd. (Price 6*s.*)

HEYROVSKÝ, J. "*Polarographisches Praktikum.*" (Anleitungen für die chemische Laboratoriumspraxis. Begründet von E. Zintl; herausgegeben von R. Brill. Band IV). 8vo, pp. vi + 118. Illustrated. Berlin, Göttingen, Heidelberg, 1948: Springer-Verlag. (Price DM 8.40)

KAPPEN, H. "*Die Hochofenschlacke (Hüttenkalk) als Mittel zur Verbesserung des Bodens und zur Steigerung der Ernten.*" 8vo, pp. 156. Berlin and Hamburg, 1950: Paul Parey, Verlag für Landwirtschaft, Gartenbau und Forstwesen. (Price DM 14.40)

KRAMER, J. "*Der metallische Zustand.*" Pp. 147. Göttingen, 1950: Verlag Vandenhoeck & Ruprecht. (Price DM 14.80)

KRAUSE, H. "*Die Betriebsüberwachung und Untersuchung galvanischer Bäder und Niederschläge.*" 2. Auflage. 8vo, pp. 251. Illustrated. Munich, 1949: Carl Hanser Verlag. (Price, bound DM 15.–, unbound DM 12.80)

LETHERSICH, W. "*Impact Testing: Critical Résumé.*" (British Electrical and Allied Industries Research Association, Technical Report No. L/T 186). Leatherhead: The Association. (Price 12*s.*)

LETHERSICH, W. and H. PELZER. "*The Measurement of the Coefficient of Internal Friction of Solid Rods by a Resonance Method.*" (British Electrical and Allied Industries Research Association, Technical Report No. L/T 213). Leatherhead: The Association. (Price 6*s.*)

LÜTH, F. "*Gesichtspunkte für Bestellung, Abnahme und Beurteilung hüttenmännischer Glüh- und Wärmöfen.*" (Mitteilung Nr. 360 der Wärmestelle des VDEh). 4to, pp. 18. Düsseldorf, 1950: Verlag Stahleisen m.b.H. (Price DM 2.80)

MALISIUS, R. "*Der Weg zum wirtschaftlichen Schweissen.*" 8vo, pp. 158. Illustrated. Halle (Saale) 1949: Carl Marhold-Verlagsbuchhandlung. (Price, bound DM 6.20, unbound DM 5.30)

MANTELL, C. L. "*Industrial Electrochemistry.*" Third Revised Edition. Pp. 781. New York and London, 1950: McGraw-Hill Book Co., Inc. (Price $7.50, 64*s.*)

MARTIN, T. "*Faraday's Discovery of Electro-Magnetic Induction.*" 8vo, pp. 160. Illustrated. London, 1949: Edward Arnold and Co. (Price 9*s.*)

MICHELL, F. B. "*The Practice of Mineral Dressing.*" London: The Electrical Press, Ltd. (Price 30*s.*)

MOLLOY, E. "*Gas Welders' Tables and Data.*" London: George Newnes, Ltd. (Price 5*s.*)

PORTEVIN. "*Annexes au Cours de Métallographie.*" Ecole Supérieure de Fonderie. Année 1948. La. 4to. Pp. 467 + xxii. Illustrated. Paris: Centre de Documentation Universitaire. [In 2 vols.]

RAISTRICK, A. "*Quakers in Science and Industry.*" 8vo, pp. 364. Illustrated. London, 1950: Bannisdale Press. (Price 21*s.*)

REINER, M. "*Research on the Work-Hardening of Polycrystalline Metal.*" Pp. 42. New York, 1949: Interscience Publishers, Inc. (Price $1.25)

SCHROCK, E. M. "*Quality Control and Statistical Methods.*" Pp. xi + 218. New York: Reinhold Publishing Corp. (Price $5.00)

SCHWARTZ, H. A. "*Foundry Science.*" Pp. 286. New York: Pitman Publishing Corporation. (Price $6.50)

STEINER, K. "*Oil Burners.*" Second Edition. 8vo, pp. xx + 502. Illustrated. New York, Toronto, London, 1950: McGraw-Hill Book Company, Inc. (Price $6.50)

TEED, P. LITHERLAND. *The Properties of Metallic Materials at Low Temperatures.*" (Monographs on Metallic Materials. Volume 1). 8vo, pp. viii + 222. Illustrated. London, 1950: Chapman and Hall, Ltd. (Price 21*s.*)

UNDERWOOD, L. R. "*The Rolling of Metals. Theory and Experiment.*" Volume I. With a foreword by Sir Andrew McCance. 8vo, pp. xv + 344. Illustrated. London, 1950: Chapman and Hall, Ltd. (Price 42*s.*)

WOLDMAN, N. E. "*Materials Engineering of Metal Products.*" 8vo, pp. v + 583. Illustrated. New York: Reinhold Publishing Corporation.

WORRILOW, W. H. "*A History of Steel Casting.*" 8vo, pp. 168. Cleveland, Ohio: Steel Founders' Society of America. (Price $2.50)

WUTTKE, F. "*Die Grauguss-Gasschweissung leicht gemacht!*" Praktische Ratschläge für den Schweisser. 8vo, pp. 90. Illustrated. Halle (Saale), 1950: Carl Marhold-Verlagsbuchhandlung. (Price DM 6.75)